

Charm-strange baryon strong decays in a chiral quark model

Lei-Hua Liu, Li-Ye Xiao and Xian-Hui Zhong *

Department of Physics, Hunan Normal University, and Key Laboratory of Low-Dimensional Quantum Structures and Quantum Control of Ministry of Education, Changsha 410081, China

The strong decays of charm-strange baryons up to $N = 2$ shell are studied in a chiral quark model. The theoretical predictions for the well determined charm-strange baryons, $\Xi_c^*(2645)$, $\Xi_c(2790)$ and $\Xi_c(2815)$, are in good agreement with the experimental data. This model is also extended to analyze the strong decays of the other newly observed charm-strange baryons $\Xi_c(2930)$, $\Xi_c(2980)$, $\Xi_c(3055)$, $\Xi_c(3080)$ and $\Xi_c(3123)$. Our predictions are given as follows. (i) $\Xi_c(2930)$ might be the first P -wave excitation of Ξ_c' with $J^P = 1/2^-$, favors the $|\Xi_c' {}^2P_{\lambda}1/2^- \rangle$ or $|\Xi_c' {}^4P_{\lambda}1/2^- \rangle$ state. (ii) $\Xi_c(2980)$ might correspond to two overlapping P -wave states $|\Xi_c' {}^2P_{\rho}1/2^- \rangle$ and $|\Xi_c' {}^2P_{\rho}3/2^- \rangle$, respectively. The $\Xi_c(2980)$ observed in the $\Lambda_c^+ \bar{K} \pi$ final state is most likely to be the $|\Xi_c' {}^2P_{\rho}1/2^- \rangle$ state, while the narrower resonance with a mass $m \simeq 2.97$ GeV observed in the $\Xi_c^*(2645)\pi$ channel favors to be assigned to the $|\Xi_c' {}^2P_{\rho}3/2^- \rangle$ state. (iii) $\Xi_c(3080)$ favors to be classified as the $|\Xi_c S_{\rho\rho}1/2^+ \rangle$ state, i.e., the first radial excitation ($2S$) of Ξ_c . (iv) $\Xi_c(3055)$ is most likely to be the first D -wave excitation of Ξ_c with $J^P = 3/2^+$, favors the $|\Xi_c {}^2D_{\lambda\lambda}3/2^+ \rangle$ state. (v) $\Xi_c(3123)$ might be assigned to the $|\Xi_c' {}^4D_{\lambda\lambda}3/2^+ \rangle$, $|\Xi_c' {}^4D_{\lambda\lambda}5/2^+ \rangle$, or $|\Xi_c {}^2D_{\rho\rho}5/2^+ \rangle$ state. As a by-product, we calculate the strong decays of the bottom baryons Σ_b^+ , Σ_b^0 and Ξ_b^0 , which are in good agreement with the recent observations as well.

PACS numbers: 12.39.Jh, 13.30.-a, 14.20.Lq, 14.20.Mr

I. INTRODUCTION

In recent years, several new charm-strange baryons, $\Xi_c(2930)$, $\Xi_c(2980)$, $\Xi_c(3055)$, $\Xi_c(3080)$ and $\Xi_c(3123)$, have been observed. Their experimental information has been collected in Tab. I. $\Xi_c(2980)$ and $\Xi_c(3080)$ are relatively well-established in experiments. Both of their isospin states were observed by Belle Collaboration in the $\Lambda_c^+ \bar{K} \pi$ channel [1], and confirmed by BaBar with high statistical significances [2]. Belle also observed a resonance structure around 2.97 GeV with a narrow width of ~ 18 MeV in the $\Xi_c^*(2645)\pi$ decay channel in a separate study [3], which is often considered as the same resonance, $\Xi_c(2980)$, observed in the $\Lambda_c^+ \bar{K} \pi$ channel. $\Xi_c(2930)$ was found by BaBar in the $\Lambda_c^+ K^-$ final state by analyzing the $B^- \rightarrow \Lambda_c^+ \bar{K}^- K^-$ process [4]. However, this structure is not yet confirmed by Belle. $\Xi_c(3055)^+$ and $\Xi_c(3123)^+$ were only observed by BaBar in the $\Lambda_c^+ K^- \pi^+$ final state with statistical significances of 6.4σ and 3.0σ , respectively [2]. No further evidences of them were found when BaBar searched the inclusive $\Lambda_c^+ \bar{K}$ and $\Lambda_c^+ \bar{K} \pi^+ \pi^-$ invariant mass spectra for new narrow states. BaBar's observations show that $\Xi_c(3055)^+$ and $\Xi_c(3123)^+$ mostly decay through the intermediate resonant modes $\Sigma_c(2455)^{++} K^-$ and $\Sigma_c(2520)^{++} K^-$, respectively. A good review of the recent experimental results on charmed baryons can be found in [5].

Charmed baryon mass spectroscopy has been investigated in various models [7–17]. The masses of charm-strange baryons in the $N \leq 2$ shell predicted within several quark models have been collected in Tabs. II and III. Comparing the experimental data with the quark model predictions, one finds that $\Xi_c(2930)$ could be a candidate of the $2S$ excitation of Ξ_c with $J^P = 1/2^+$, or the $1P$ excitation of Ξ_c' with $J^P = 1/2^-$, $3/2^-$ or $5/2^-$. $\Xi_c(2980)$ might be assigned to the $2S$ excitation

of Ξ_c or Ξ_c' with $J^P = 1/2^+$. $\Xi_c(3055)$ and $\Xi_c(3080)$ are most likely to be the $1D$ excitations of Ξ_c with $J^P = 3/2^+$ or $5/2^+$, or the $2S$ excitation of Ξ_c' with $J^P = 1/2^+$. $\Xi_c(3123)$ might be classified as $1D$ excitation of Ξ_c' with $J^P = 3/2^+$, $5/2^+$ or $7/2^+$. Obviously, only depending on the mass analysis it is difficult to determine the quantum numbers of these newly observed charm-strange baryons. On the other hand, the strong decays of these newly observed charm-strange baryons have been studied in the framework of heavy hadron chiral perturbation theory [18] and 3P_0 model [19, 20], respectively. In [18], Cheng and Chua advocated that the J^P numbers of $\Xi_c(2980)$ and $\Xi_c(3080)$ could be $1/2^+$ and $5/2^+$, respectively. They claimed that under this J^P assignment, it is easy to understand why $\Xi_c(2980)$ is broader than $\Xi_c(3080)$. In [19, 20], Chen *et al.* have analyzed the strong decays of the $N = 2$ shell excited charm-strange baryons in the 3P_0 model, they could only exclude some assignments according to the present experimental information. As a whole, although the new charm-strange baryons have been studied in several aspects, such as mass spectroscopy and strong decays, their quantum numbers are not clear so far. Thus, more investigations of these new heavy baryons are needed.

To further understand the nature of these newly observed charm-strange baryons, in this work, we make a systematic study of their strong decays in a chiral quark model, which has been developed and successfully used to deal with the strong decays of charmed baryons and heavy-light mesons [21–24]. It should be pointed out that very recently, some important progresses in the observation of the bottom baryons have been achieved in experiments as well: CDF Collaboration first measured the natural widths of the bottom baryons Σ_b^+ and Σ_b^0 , and improved the measurement masses [25], and CMS Collaboration observed a new neutral excited bottom baryon with a mass $m = 5945.0 \pm 0.7 \pm 0.3 \pm 2.7$ MeV, which is most likely to be the Ξ_b^{*0} [26]. As a by-product, in this work we also calculate the strong decays of these bottom baryons according to the new measurements.

*E-mail: zhongxh@hunnu.edu.cn

This work is organized as follows. In the subsequent section, the charm-strange baryon in the quark model is outlined. Then a brief review of the chiral quark model approach is

given in Sec. III. The numerical results are presented and discussed in Sec. IV. Finally, a summary is given in Sec. V.

TABLE I: Summary of the experimental results of the newly observed charm-strange baryons.

Resonance	Mass (MeV)	Width (MeV)	Observed decay channel	Collaboration	Status [6]
$\Xi_c(2930)^0$	$2931 \pm 3 \pm 5$	$36 \pm 7 \pm 11$	$\Lambda_c^+ K^-$	BaBar [4]	*
$\Xi_c(2980)^+$	$2978.5 \pm 2.1 \pm 2.0$	$43.5 \pm 7.5 \pm 7.0$	$\Lambda_c^+ K^- \pi^+$	Belle [1]	***
	$2969.3 \pm 2.2 \pm 1.7$	$27 \pm 8 \pm 2$	$\Lambda_c^+ K^- \pi^+, \Sigma_c(2455)^{++} K^-$	BaBar [2]	
	$2967.7 \pm 2.3^{+1.1}_{-1.2}$	$18 \pm 6 \pm 3$	$\Xi_c(2645)^0 \pi^+$	Belle [3]	
$\Xi_c(2980)^0$	$2977.1 \pm 8.8 \pm 3.5$	43.5 fixed	$\Lambda_c^+ \bar{K}^0 \pi^-$	Belle [1]	***
	$2972.9 \pm 4.4 \pm 1.6$	$31 \pm 7 \pm 8$	$\Lambda_c^+ \bar{K}^0 \pi^-$	BaBar [2]	
	$2965.7 \pm 2.4^{+1.1}_{-1.2}$	$15 \pm 6 \pm 3$	$\Xi_c(2645)^+ \pi^-$	Belle [3]	
$\Xi_c(3055)^+$	$3054.2 \pm 1.2 \pm 0.5$	$17 \pm 6 \pm 11$	$\Sigma_c(2455)^{++} K^-$	BaBar [2]	**
$\Xi_c(3080)^+$	$3076.7 \pm 0.9 \pm 0.5$	$6.2 \pm 1.2 \pm 0.8$	$\Lambda_c^+ K^- \pi^+$	Belle [1]	***
	$3077.0 \pm 0.4 \pm 0.2$	$5.5 \pm 1.3 \pm 0.6$	$\Lambda_c^+ K^- \pi^+, \Sigma_c(2455, 2520)^{++} K^-$	BaBar [2]	
$\Xi_c(3080)^0$	$3082.8 \pm 1.8 \pm 1.5$	$5.2 \pm 3.1 \pm 1.8$	$\Lambda_c^+ \bar{K}^0 \pi^-$	Belle [1]	***
	$3079.3 \pm 1.1 \pm 0.2$	$5.9 \pm 2.3 \pm 1.5$	$\Lambda_c^+ \bar{K}^0 \pi^-, \Sigma_c(2455, 2520)^0 K_S^0$	BaBar [2]	
$\Xi_c(3123)^+$	$3122.9 \pm 1.3 \pm 0.3$	$4.4 \pm 3.4 \pm 1.7$	$\Sigma_c(2520)^{++} K^-$	BaBar [2]	*

II. CHARM-STRANGE BARYON IN THE QUARK MODEL

The charmed baryon contains a heavy charm quark, which violates SU(4) symmetry. However, the SU(3) symmetry between the other two light quarks (u , d , or s) is approximately kept. According to the symmetry, the charmed baryons can be classified two different SU(3) flavor representations: the symmetric **6** and antisymmetric antitriplet $\bar{\mathbf{3}}$. For the charm-strange baryon, the antisymmetric flavor wave function (Ξ_c -type) can be written as

$$\phi_{\Xi_c} = \begin{cases} \frac{1}{\sqrt{2}}(us - su)c & \text{for } \Xi_c^+ \\ \frac{1}{\sqrt{2}}(ds - sd)c & \text{for } \Xi_c^0 \end{cases}, \quad (1)$$

while the symmetric flavor wave function (Ξ'_c -type) is given by

$$\phi_{\Xi'_c} = \begin{cases} \frac{1}{\sqrt{2}}(us + su)c & \text{for } \Xi'^+_c \\ \frac{1}{\sqrt{2}}(ds + sd)c & \text{for } \Xi'^0_c \end{cases}. \quad (2)$$

In the quark model, the typical SU(2) spin wave functions for the charm-strange baryons can be adopted [27, 28], which are

$$\begin{aligned} \chi^s_{3/2} &= \uparrow\uparrow\uparrow, \quad \chi^s_{-3/2} = \downarrow\downarrow\downarrow, \\ \chi^s_{1/2} &= \frac{1}{\sqrt{3}}(\uparrow\uparrow\downarrow + \uparrow\downarrow\uparrow + \downarrow\uparrow\uparrow), \\ \chi^s_{-1/2} &= \frac{1}{\sqrt{3}}(\uparrow\downarrow\downarrow + \downarrow\downarrow\uparrow + \downarrow\uparrow\downarrow), \end{aligned} \quad (3)$$

TABLE II: Masses (MeV) of the Ξ_c -type charm-strange baryons in the various quark models.

N	J^P	State	[13]	[16]	[15]	[12]	[17]
0	$\frac{1}{2}^+$	1S	2471	2476	2467	2466	2481
1	$\frac{1}{2}^-$	1P	2799	2792	2792	2773	2801
1	$\frac{3}{2}^-$	1P	...	2819	2792	2783	2820
2	$\frac{1}{2}^+$	2S	3137	2959	2992	...	2923
2	$\frac{3}{2}^+$	1D	3071	3059	3057	3012	3030
2	$\frac{5}{2}^+$	1D	3049	3076	3057	3004	3042

for the spin-3/2 states with a symmetric spin wave function,

$$\begin{aligned} \chi^{\rho}_{1/2} &= \frac{1}{\sqrt{2}}(\uparrow\downarrow\uparrow - \downarrow\uparrow\uparrow), \\ \chi^{\rho}_{-1/2} &= \frac{1}{\sqrt{2}}(\uparrow\downarrow\downarrow - \downarrow\uparrow\downarrow), \end{aligned} \quad (4)$$

for the spin-1/2 states with a mixed antisymmetric spin wave function, and

$$\begin{aligned} \chi^{\lambda}_{1/2} &= -\frac{1}{\sqrt{6}}(\uparrow\downarrow\uparrow + \downarrow\uparrow\uparrow - 2\uparrow\uparrow\downarrow), \\ \chi^{\lambda}_{-1/2} &= \frac{1}{\sqrt{6}}(\uparrow\downarrow\downarrow + \downarrow\uparrow\downarrow - 2\downarrow\downarrow\uparrow), \end{aligned} \quad (5)$$

for the spin-1/2 states with a mixed symmetric spin wave function.

The spatial wave function of a charm-strange baryon is adopted the harmonic oscillator form in the constituent quark

TABLE III: Masses (MeV) of the Ξ'_c -type charm-strange baryons in the various quark models.

N	J^P	State	[13]	[16]	[15]	[12]	[17]
0	$\frac{1}{2}^+$	1S	2574	2579	2567	2594	2578
0	$\frac{3}{2}^+$	1S	2642	2649	2647	2649	2654
1	$\frac{1}{2}^-$	1P	2902	2936	2897	2855	2934
1	$\frac{3}{2}^-$	1P	...	2935	2910	2866	2931
1	$\frac{5}{2}^-$	1P	...	2929	3050	2895	2921
2	$\frac{1}{2}^+$	2S	3212	2983	3087	...	2984
2	$\frac{3}{2}^+$	1D	...	3163	...	...	3132
2	$\frac{5}{2}^+$	1D	...	3160	3127	...	3127
2	$\frac{7}{2}^+$	1D	3132	3166	3167	3080	3123
2	$\frac{9}{2}^+$	1D	...	3147	...	3094	3136

model. The details of the spatial wave functions can be found in our previous work [21].

The spin-flavor and spatial wave functions of baryons must be symmetric since the color wave function is antisymmetric. The flavor wave functions of the Ξ_c -type charm-strange baryons, ϕ_{Ξ_c} , are antisymmetric under the interchange of the u (d) and s quarks, thus, their spin-space wave functions must be symmetric. In contrast, the spin-spatial wave functions of Ξ'_c -type charm-strange baryons are required to be antisymmetric due to their symmetric flavor wave functions under the interchange of the two light quarks. The notations, wave functions, and quantum numbers of the Ξ_c -type and Ξ'_c -type charm-strange baryons up to $N = 2$ shell classified in the quark model are listed in Tabs. IV and V, respectively.

TABLE IV: The Ξ_c -type charm-strange baryons classified in the quark model and their possible two body strong decay channels. The notation of the Ξ_c -type charmed baryon is denoted by $|\Xi_c^{2S+1} L_{\sigma} J^P\rangle$ as used in Ref. [27]. The Clebsch-Gordan series for the spin and angular-momentum addition $|\Xi_c^{2S+1} L_{\sigma} J^P\rangle = \sum_{L_z+S_z=J_z} \langle LL_z, SS_z | JJ_z \rangle^N \Psi_{LL_z}^{\sigma} \chi_{S_z} \phi_{\Xi_c}$ has been omitted.

Notation	N	l_λ	l_ρ	L	S	J^P	Wave function	Strong decay channel
$|\Xi_c^{2S} \frac{1}{2}^+\rangle$	0	0	0	0	$\frac{1}{2}$	$\frac{1}{2}^+$	${}^0\Psi_{00}^S \chi_{S_z}^{\rho} \phi_{\Xi_c}$	...
$|\Xi_c^{2P} \frac{1}{2}^-\rangle$	1	1	0	1	$\frac{1}{2}$	$\frac{1}{2}^-$	${}^1\Psi_{1L_c}^{\lambda} \chi_{S_z}^{\rho} \phi_{\Xi_c}$	$\Xi'_c \pi, \Xi_c^* \pi$
$|\Xi_c^{2P} \frac{3}{2}^-\rangle$	1	1	0	1	$\frac{1}{2}$	$\frac{3}{2}^-$	${}^1\Psi_{1L_c}^{\lambda} \chi_{S_z}^{\rho} \phi_{\Xi_c}$	$\Xi_c \pi, \Xi'_c \pi, \Xi_c^* \pi$
$|\Xi_c^{2P} \frac{1}{2}^-\rangle$	1	0	1	1	$\frac{1}{2}$	$\frac{1}{2}^-$	${}^1\Psi_{1L_c}^{\rho} \chi_{S_z}^{\lambda} \phi_{\Xi_c}$	$\Xi_c \pi, \Xi'_c \pi, \Xi_c^* \pi$
$|\Xi_c^{2P} \frac{3}{2}^-\rangle$	1	0	1	1	$\frac{1}{2}$	$\frac{3}{2}^-$	${}^1\Psi_{1L_c}^{\rho} \chi_{S_z}^{\lambda} \phi_{\Xi_c}$	$\Xi_c \pi, \Xi'_c \pi, \Xi_c^* \pi$
$|\Xi_c^{4P} \frac{1}{2}^-\rangle$	1	0	1	1	$\frac{3}{2}$	$\frac{1}{2}^-$	${}^1\Psi_{1L_c}^{\rho} \chi_{S_z}^{\lambda} \phi_{\Xi_c}$	$\Xi_c \pi, \Xi'_c \pi, \Xi_c^* \pi$
$|\Xi_c^{4P} \frac{3}{2}^-\rangle$	1	0	1	1	$\frac{3}{2}$	$\frac{3}{2}^-$	${}^1\Psi_{1L_c}^{\rho} \chi_{S_z}^{\lambda} \phi_{\Xi_c}$	$\Xi_c \pi, \Xi'_c \pi, \Xi_c^* \pi$
$|\Xi_c^{4P} \frac{5}{2}^-\rangle$	1	0	1	1	$\frac{3}{2}$	$\frac{5}{2}^-$	${}^1\Psi_{1L_c}^{\rho} \chi_{S_z}^{\lambda} \phi_{\Xi_c}$	$\Xi_c \pi, \Xi'_c \pi, \Xi_c^* \pi$
$|\Xi_c^{2S} \frac{1}{2}^+\rangle$	2	1	1	0	$\frac{1}{2}$	$\frac{1}{2}^+$	${}^2\Psi_{00}^A \chi_{S_z}^{\lambda} \phi_{\Xi_c}$	$\Xi_c \pi, \Xi_c \eta, \Lambda_c K, \Xi'_c \pi, \Sigma_c K, \Xi_c^* \pi, \Sigma_c^* K, \Xi_c(2790, 2815) \pi$
$|\Xi_c^{4S} \frac{3}{2}^+\rangle$	2	1	1	0	$\frac{3}{2}$	$\frac{3}{2}^+$	${}^2\Psi_{00}^A \chi_{S_z}^{\lambda} \phi_{\Xi_c}$	$\Xi_c \pi, \Xi_c \eta, \Lambda_c K, \Xi'_c \pi, \Sigma_c K, \Xi_c^* \pi, \Sigma_c^* K, \Xi_c(2790, 2815) \pi$
$|\Xi_c^{2P} \frac{1}{2}^+\rangle$	2	1	1	1	$\frac{1}{2}$	$\frac{1}{2}^+$	${}^2\Psi_{1L_c}^A \chi_{S_z}^{\lambda} \phi_{\Xi_c}$	$\Xi_c \pi, \Xi_c \eta, \Lambda_c K, \Xi'_c \pi, \Sigma_c K, \Xi_c^* \pi, \Sigma_c^* K, \Xi_c(2790, 2815) \pi$
$|\Xi_c^{2P} \frac{3}{2}^+\rangle$	2	1	1	1	$\frac{1}{2}$	$\frac{3}{2}^+$	${}^2\Psi_{1L_c}^A \chi_{S_z}^{\lambda} \phi_{\Xi_c}$	$\Xi_c \pi, \Xi_c \eta, \Lambda_c K, \Xi'_c \pi, \Sigma_c K, \Xi_c^* \pi, \Sigma_c^* K, \Xi_c(2790, 2815) \pi$
$|\Xi_c^{4P} \frac{1}{2}^+\rangle$	2	1	1	1	$\frac{3}{2}$	$\frac{1}{2}^+$	${}^2\Psi_{1L_c}^A \chi_{S_z}^{\lambda} \phi_{\Xi_c}$	$\Xi_c \pi, \Xi_c \eta, \Lambda_c K, \Xi'_c \pi, \Sigma_c K, \Xi_c^* \pi, \Sigma_c^* K, \Xi_c(2790, 2815) \pi$
$|\Xi_c^{4P} \frac{3}{2}^+\rangle$	2	1	1	1	$\frac{3}{2}$	$\frac{3}{2}^+$	${}^2\Psi_{1L_c}^A \chi_{S_z}^{\lambda} \phi_{\Xi_c}$	$\Xi_c \pi, \Xi_c \eta, \Lambda_c K, \Xi'_c \pi, \Sigma_c K, \Xi_c^* \pi, \Sigma_c^* K, \Xi_c(2790, 2815) \pi$
$|\Xi_c^{4P} \frac{5}{2}^+\rangle$	2	1	1	1	$\frac{3}{2}$	$\frac{5}{2}^+$	${}^2\Psi_{1L_c}^A \chi_{S_z}^{\lambda} \phi_{\Xi_c}$	$\Xi_c \pi, \Xi_c \eta, \Lambda_c K, \Xi'_c \pi, \Sigma_c K, \Xi_c^* \pi, \Sigma_c^* K, \Xi_c(2790, 2815) \pi$
$|\Xi_c^{2D} \frac{3}{2}^+\rangle$	2	1	1	2	$\frac{1}{2}$	$\frac{3}{2}^+$	${}^2\Psi_{2L_c}^A \chi_{S_z}^{\lambda} \phi_{\Xi_c}$	$\Xi_c \pi, \Xi_c \eta, \Lambda_c K, \Xi'_c \pi, \Sigma_c K, \Xi_c^* \pi, \Sigma_c^* K, \Xi_c(2790, 2815) \pi$
$|\Xi_c^{2D} \frac{5}{2}^+\rangle$	2	1	1	2	$\frac{1}{2}$	$\frac{5}{2}^+$	${}^2\Psi_{2L_c}^A \chi_{S_z}^{\lambda} \phi_{\Xi_c}$	$\Xi_c \pi, \Xi_c \eta, \Lambda_c K, \Xi'_c \pi, \Sigma_c K, \Xi_c^* \pi, \Sigma_c^* K, \Xi_c(2790, 2815) \pi$
$|\Xi_c^{4D} \frac{1}{2}^+\rangle$	2	1	1	2	$\frac{3}{2}$	$\frac{1}{2}^+$	${}^2\Psi_{2L_c}^A \chi_{S_z}^{\lambda} \phi_{\Xi_c}$	$\Xi_c \pi, \Xi_c \eta, \Lambda_c K, \Xi'_c \pi, \Sigma_c K, \Xi_c^* \pi, \Sigma_c^* K, \Xi_c(2790, 2815) \pi$
$|\Xi_c^{4D} \frac{3}{2}^+\rangle$	2	1	1	2	$\frac{3}{2}$	$\frac{3}{2}^+$	${}^2\Psi_{2L_c}^A \chi_{S_z}^{\lambda} \phi_{\Xi_c}$	$\Xi_c \pi, \Xi_c \eta, \Lambda_c K, \Xi'_c \pi, \Sigma_c K, \Xi_c^* \pi, \Sigma_c^* K, \Xi_c(2790, 2815) \pi$
$|\Xi_c^{4D} \frac{5}{2}^+\rangle$	2	1	1	2	$\frac{3}{2}$	$\frac{5}{2}^+$	${}^2\Psi_{2L_c}^A \chi_{S_z}^{\lambda} \phi_{\Xi_c}$	$\Xi_c \pi, \Xi_c \eta, \Lambda_c K, \Xi'_c \pi, \Sigma_c K, \Xi_c^* \pi, \Sigma_c^* K, \Xi_c(2790, 2815) \pi$
$|\Xi_c^{4D} \frac{7}{2}^+\rangle$	2	1	1	2	$\frac{3}{2}$	$\frac{7}{2}^+$	${}^2\Psi_{2L_c}^A \chi_{S_z}^{\lambda} \phi_{\Xi_c}$	$\Xi_c \pi, \Xi_c \eta, \Lambda_c K, \Xi'_c \pi, \Sigma_c K, \Xi_c^* \pi, \Sigma_c^* K, \Xi_c(2790, 2815) \pi$
$|\Xi_c^{2D} \frac{3}{2}^+\rangle$	2	0	2	2	$\frac{1}{2}$	$\frac{3}{2}^+$	${}^2\Psi_{2L_c}^{\rho\rho} \chi_{S_z}^{\rho} \phi_{\Xi_c}$	$\Xi'_c \pi, \Sigma_c K, \Xi_c^* \pi, \Sigma_c^* K$
$|\Xi_c^{2D} \frac{5}{2}^+\rangle$	2	0	2	2	$\frac{1}{2}$	$\frac{5}{2}^+$	${}^2\Psi_{2L_c}^{\rho\rho} \chi_{S_z}^{\rho} \phi_{\Xi_c}$	$\Xi'_c \pi, \Sigma_c K, \Xi_c^* \pi, \Sigma_c^* K, D\Lambda$
$|\Xi_c^{2D} \frac{3}{2}^+\rangle$	2	2	0	2	$\frac{1}{2}$	$\frac{3}{2}^+$	${}^2\Psi_{2L_c}^{\lambda\lambda} \chi_{S_z}^{\rho} \phi_{\Xi_c}$	$\Xi'_c \pi, \Sigma_c K, \Xi_c^* \pi, \Sigma_c^* K, D\Lambda$
$|\Xi_c^{2D} \frac{5}{2}^+\rangle$	2	2	0	2	$\frac{1}{2}$	$\frac{5}{2}^+$	${}^2\Psi_{2L_c}^{\lambda\lambda} \chi_{S_z}^{\rho} \phi_{\Xi_c}$	$\Xi'_c \pi, \Sigma_c K, \Xi_c^* \pi, \Sigma_c^* K, D\Lambda$
$|\Xi_c^{2S} \frac{1}{2}^+\rangle$	2	0	0	0	$\frac{1}{2}$	$\frac{1}{2}^+$	${}^2\Psi_{00}^{\rho\rho} \chi_{S_z}^{\rho} \phi_{\Xi_c}$	$\Xi'_c \pi, \Sigma_c K, \Xi_c^* \pi, \Sigma_c^* K$
$|\Xi_c^{2S} \frac{1}{2}^+\rangle$	2	0	0	0	$\frac{1}{2}$	$\frac{1}{2}^+$	${}^2\Psi_{00}^{\lambda\lambda} \chi_{S_z}^{\rho} \phi_{\Xi_c}$	$\Xi'_c \pi, \Sigma_c K, \Xi_c^* \pi, \Sigma_c^* K, D\Lambda$

TABLE V: The Ξ'_c -type charm-strange baryons classified in the quark model and their possible two body strong decay channels. The notation of the Ξ'_c -type charmed baryon is denoted by $|\Xi'_c{}^{2S+1}L_G J^P\rangle$ as used in Ref. [27]. The Clebsch-Gordan series for the spin and angular-momentum addition $|\Xi'_c{}^{2S+1}L_G J^P\rangle = \sum_{L_c+S_z=J_z} \langle LL_z, SS_z | JJ_z \rangle {}^N\Psi_{LL_c}^{\sigma} \chi_{S_z} \phi_{\Xi'_c}$ has been omitted.

Notation	N	l_λ	l_ρ	L	S	J^P	Wave function	Strong decay channel
$|\Xi'_c{}^2S\frac{1}{2}^+\rangle$	0	0	0	0	$\frac{1}{2}$	$\frac{1}{2}^+$	${}^0\Psi_{00}^S \chi_{S_z}^A \phi_{\Xi'_c}$	...
$|\Xi'_c{}^4S\frac{3}{2}^+\rangle$	0	0	0	0	$\frac{3}{2}$	$\frac{3}{2}^+$	${}^0\Psi_{00}^S \chi_{S_z}^S \phi_{\Xi'_c}$	$\Xi_c \pi$
$|\Xi'_c{}^2P_{\Lambda}\frac{1}{2}^-\rangle$	1	1	0	1	$\frac{1}{2}$	$\frac{1}{2}^-$	${}^1\Psi_{1L_c}^{\Lambda} \chi_{S_z}^A \phi_{\Xi'_c}$	$\Xi_c \pi, \Lambda_c K, \Xi'_c \pi, \Sigma_c K, \Xi_c^* \pi, \Sigma_c^* K, \Xi_c(2790, 2815) \pi$
$|\Xi'_c{}^2P_{\Lambda}\frac{3}{2}^-\rangle$	1	1	0	1	$\frac{1}{2}$	$\frac{3}{2}^-$		
$|\Xi'_c{}^4P_{\Lambda}\frac{1}{2}^-\rangle$	1	1	0	1	$\frac{3}{2}$	$\frac{1}{2}^-$		
$|\Xi'_c{}^4P_{\Lambda}\frac{3}{2}^-\rangle$	1	1	0	1	$\frac{3}{2}$	$\frac{3}{2}^-$	${}^1\Psi_{1L_c}^{\Lambda} \chi_{S_z}^S \phi_{\Xi'_c}$	$\Xi_c \pi, \Lambda_c K, \Xi'_c \pi, \Sigma_c K, \Xi_c^* \pi, \Sigma_c^* K, \Xi_c(2790, 2815) \pi$
$|\Xi'_c{}^4P_{\Lambda}\frac{5}{2}^-\rangle$	1	1	0	1	$\frac{3}{2}$	$\frac{5}{2}^-$		
$|\Xi'_c{}^2P_{\rho}\frac{1}{2}^-\rangle$	1	0	1	1	$\frac{1}{2}$	$\frac{1}{2}^-$	${}^1\Psi_{1L_c}^{\rho} \chi_{S_z}^{\rho} \phi_{\Xi'_c}$	$\Xi'_c \pi, \Sigma_c K, \Xi_c^* \pi, \Sigma_c^* K$
$|\Xi'_c{}^2P_{\rho}\frac{3}{2}^-\rangle$	1	0	1	1	$\frac{1}{2}$	$\frac{3}{2}^-$		
$|\Xi'_c{}^2S_{\Lambda}\frac{1}{2}^+\rangle$	2	1	1	0	$\frac{1}{2}$	$\frac{1}{2}^+$	${}^2\Psi_{00}^{\Lambda} \chi_{S_z}^{\rho} \phi_{\Xi'_c}$	$\Xi'_c \pi, \Sigma_c K, \Xi_c^* \pi, \Sigma_c^* K$
$|\Xi'_c{}^2P_{\Lambda}\frac{1}{2}^+\rangle$	2	1	1	1	$\frac{1}{2}$	$\frac{1}{2}^+$	${}^2\Psi_{1L_c}^{\Lambda} \chi_{S_z}^{\rho} \phi_{\Xi'_c}$	$\Xi'_c \pi, \Sigma_c K, \Xi_c^* \pi, \Sigma_c^* K$
$|\Xi'_c{}^2P_{\Lambda}\frac{3}{2}^+\rangle$	2	1	1	1	$\frac{1}{2}$	$\frac{3}{2}^+$		
$|\Xi'_c{}^2D_{\Lambda}\frac{3}{2}^+\rangle$	2	1	1	2	$\frac{1}{2}$	$\frac{3}{2}^+$		
$|\Xi'_c{}^2D_{\Lambda}\frac{5}{2}^+\rangle$	2	1	1	2	$\frac{1}{2}$	$\frac{5}{2}^+$	${}^2\Psi_{2L_c}^{\Lambda} \chi_{S_z}^{\rho} \phi_{\Xi'_c}$	$\Xi'_c \pi, \Sigma_c K, \Xi_c^* \pi, \Sigma_c^* K$
$|\Xi'_c{}^2D_{\rho\rho}\frac{3}{2}^+\rangle$	2	0	2	2	$\frac{1}{2}$	$\frac{3}{2}^+$		
$|\Xi'_c{}^2D_{\rho\rho}\frac{5}{2}^+\rangle$	2	0	2	2	$\frac{1}{2}$	$\frac{5}{2}^+$	${}^2\Psi_{2L_c}^{\rho\rho} \chi_{S_z}^{\Lambda} \phi_{\Xi'_c}$	$\Xi_c \pi, \Xi_c \eta, \Lambda_c K, \Xi'_c \pi, \Sigma_c K, \Xi_c^* \pi, \Sigma_c^* K, \Xi_c(2790, 2815) \pi$
$|\Xi'_c{}^4D_{\rho\rho}\frac{1}{2}^+\rangle$	2	0	2	2	$\frac{3}{2}$	$\frac{1}{2}^+$		
$|\Xi'_c{}^4D_{\rho\rho}\frac{3}{2}^+\rangle$	2	0	2	2	$\frac{3}{2}$	$\frac{3}{2}^+$	${}^2\Psi_{2L_c}^{\rho\rho} \chi_{S_z}^S \phi_{\Xi'_c}$	$\Xi_c \pi, \Xi_c \eta, \Lambda_c K, \Xi'_c \pi, \Sigma_c K, \Xi_c^* \pi, \Sigma_c^* K, \Xi_c(2790, 2815) \pi$
$|\Xi'_c{}^4D_{\rho\rho}\frac{5}{2}^+\rangle$	2	0	2	2	$\frac{3}{2}$	$\frac{5}{2}^+$		
$|\Xi'_c{}^4D_{\rho\rho}\frac{7}{2}^+\rangle$	2	0	2	2	$\frac{3}{2}$	$\frac{7}{2}^+$		
$|\Xi'_c{}^2D_{\Lambda\Lambda}\frac{3}{2}^+\rangle$	2	2	0	2	$\frac{1}{2}$	$\frac{3}{2}^+$		
$|\Xi'_c{}^2D_{\Lambda\Lambda}\frac{5}{2}^+\rangle$	2	2	0	2	$\frac{1}{2}$	$\frac{5}{2}^+$	${}^2\Psi_{2L_c}^{\Lambda\Lambda} \chi_{S_z}^{\Lambda} \phi_{\Xi'_c}$	$\Xi_c \pi, \Xi_c \eta, \Lambda_c K, \Xi'_c \pi, \Sigma_c K, \Xi_c^* \pi, \Sigma_c^* K, \Xi_c(2790, 2815) \pi, D\Lambda$
$|\Xi'_c{}^4D_{\Lambda\Lambda}\frac{1}{2}^+\rangle$	2	2	0	2	$\frac{3}{2}$	$\frac{1}{2}^+$		
$|\Xi'_c{}^4D_{\Lambda\Lambda}\frac{3}{2}^+\rangle$	2	2	0	2	$\frac{3}{2}$	$\frac{3}{2}^+$	${}^2\Psi_{2L_c}^{\Lambda\Lambda} \chi_{S_z}^S \phi_{\Xi'_c}$	$\Xi_c \pi, \Xi_c \eta, \Lambda_c K, \Xi'_c \pi, \Sigma_c K, \Xi_c^* \pi, \Sigma_c^* K, \Xi_c(2790, 2815) \pi, D\Lambda$
$|\Xi'_c{}^4D_{\Lambda\Lambda}\frac{5}{2}^+\rangle$	2	2	0	2	$\frac{3}{2}$	$\frac{5}{2}^+$		
$|\Xi'_c{}^4D_{\Lambda\Lambda}\frac{7}{2}^+\rangle$	2	2	0	2	$\frac{3}{2}$	$\frac{7}{2}^+$		
$|\Xi'_c{}^2S_{\rho\rho}\frac{1}{2}^+\rangle$	2	0	0	0	$\frac{1}{2}$	$\frac{1}{2}^+$	${}^2\Psi_{00}^{\rho\rho} \chi_{S_z}^{\Lambda} \phi_{\Xi'_c}$	$\Xi_c \pi, \Xi_c \eta, \Lambda_c K, \Xi'_c \pi, \Sigma_c K, \Xi_c^* \pi, \Sigma_c^* K, \Xi_c(2790, 2815) \pi$
$|\Xi'_c{}^4S_{\rho\rho}\frac{3}{2}^+\rangle$	2	0	0	0	$\frac{3}{2}$	$\frac{3}{2}^+$	${}^2\Psi_{00}^{\rho\rho} \chi_{S_z}^S \phi_{\Xi'_c}$	$\Xi_c \pi, \Xi_c \eta, \Lambda_c K, \Xi'_c \pi, \Sigma_c K, \Xi_c^* \pi, \Sigma_c^* K, \Xi_c(2790, 2815) \pi$
$|\Xi'_c{}^2S_{\Lambda\Lambda}\frac{1}{2}^+\rangle$	2	0	0	0	$\frac{1}{2}$	$\frac{1}{2}^+$	${}^2\Psi_{00}^{\Lambda\Lambda} \chi_{S_z}^{\Lambda} \phi_{\Xi'_c}$	$\Xi_c \pi, \Xi_c \eta, \Lambda_c K, \Xi'_c \pi, \Sigma_c K, \Xi_c^* \pi, \Sigma_c^* K, \Xi_c(2790, 2815) \pi$
$|\Xi'_c{}^4S_{\Lambda\Lambda}\frac{3}{2}^+\rangle$	2	0	0	0	$\frac{3}{2}$	$\frac{3}{2}^+$	${}^2\Psi_{00}^{\Lambda\Lambda} \chi_{S_z}^S \phi_{\Xi'_c}$	$\Xi_c \pi, \Xi_c \eta, \Lambda_c K, \Xi'_c \pi, \Sigma_c K, \Xi_c^* \pi, \Sigma_c^* K, \Xi_c(2790, 2815) \pi$

III. THE CHIRAL QUARK MODEL

In the chiral quark model, the effective low energy quark-meson pseudoscalar coupling at tree-level is given by [29–33]

$$H_m = \sum_j \frac{1}{f_m} \bar{\psi}_j \gamma_\mu^j \gamma_5^j \psi_j \vec{\tau} \cdot \partial^\mu \vec{\phi}_m. \quad (6)$$

where ψ_j represents the j -th quark field in a baryon and f_m is the meson's decay constant. The pseudoscalar-meson octet

ϕ_m is expressed as

$$\phi_m = \begin{pmatrix} \frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta & \pi^+ & K^+ \\ \pi^- & -\frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta & K^0 \\ K^- & \bar{K}^0 & -\sqrt{\frac{2}{3}}\eta \end{pmatrix}. \quad (7)$$

To match non-relativistic harmonic oscillator spatial wave function ${}^N\Psi_{LL_c}$ in the quark model, we adopt the non-relativistic form of Eq. (6) in the calculations, which is given by [29–33]

$$H_m^{nr} = \sum_j \left\{ \frac{\omega_m}{E_f + M_f} \sigma_j \cdot \mathbf{P}_f + \frac{\omega_m}{E_i + M_i} \sigma_j \cdot \mathbf{P}_i \right\}$$

$$-\sigma_j \cdot \mathbf{q} + \frac{\omega_m}{2\mu_q} \sigma_j \cdot \mathbf{p}'_j \} I_j \varphi_m, \quad (8)$$

where σ_j and μ_q correspond to the Pauli spin vector and the reduced mass of the j -th quark in the initial and final baryons, respectively. For emitting a meson, we have $\varphi_m = e^{-i\mathbf{q} \cdot \mathbf{r}_j}$, and for absorbing a meson we have $\varphi_m = e^{i\mathbf{q} \cdot \mathbf{r}_j}$. In the above non-relativistic expansions, $\mathbf{p}'_j = \mathbf{p}_j - m_j/M\mathbf{P}_{c.m.}$ is the internal coordinate for the j -th quark in the baryon rest frame. ω_m and \mathbf{q} are the energy and three-vector momentum of the meson, respectively. \mathbf{P}_i and \mathbf{P}_f stand for the momenta of the initial final baryons, respectively. The isospin operator I_j in Eq. (8) is expressed as

$$I_j = \begin{cases} a_j^\dagger(u)a_j(s) & \text{for } K^+, \\ a_j^\dagger(s)a_j(u) & \text{for } K^-, \\ a_j^\dagger(d)a_j(s) & \text{for } K^0, \\ a_j^\dagger(s)a_j(d) & \text{for } \bar{K}^0, \\ a_j^\dagger(u)a_j(d) & \text{for } \pi^-, \\ a_j^\dagger(d)a_j(u) & \text{for } \pi^+, \\ \frac{1}{\sqrt{2}}[a_j^\dagger(u)a_j(u) - a_j^\dagger(d)a_j(d)] & \text{for } \pi^0, \\ \frac{1}{\sqrt{2}}[a_j^\dagger(u)a_j(u) + a_j^\dagger(d)a_j(d)] \cos \phi_P & \\ -a_j^\dagger(s)a_j(s) \sin \phi_P & \text{for } \eta, \end{cases} \quad (9)$$

where $a_j^\dagger(u, d, s)$ and $a_j(u, d, s)$ are the creation and annihilation operators for the u , d and s quarks, and ϕ_P is the mixing angle of η meson in the flavor basis [6, 34].

For a light pseudoscalar meson emission in a baryon strong decays, the partial decay amplitudes can be worked out according to the non-relativistic operator of quark-meson coupling. The details of how to work out the decay amplitudes can be seen in our previous work [21]. The quark model permitted two body strong decay channels of each charm-strange baryon have been listed in Tabs. IV and V as well. With the partial decay amplitudes derived from the chiral quark model, we can calculate the strong decay width by

$$\Gamma = \left(\frac{\delta}{f_m} \right)^2 \frac{(E_f + M_f)|\mathbf{q}|}{4\pi M_i(2J_i + 1)} \sum_{J_{iz}, J_{fz}} |\mathcal{M}_{J_{iz}, J_{fz}}|^2, \quad (10)$$

where $\mathcal{M}_{J_{iz}, J_{fz}}$ is the transition amplitude, J_{iz} and J_{fz} stand for the third components of the total angular momenta of the initial and final baryons, respectively. δ as a global parameter accounts for the strength of the quark-meson couplings. It has been determined in our previous study of the strong decays of the charmed baryons and heavy-light mesons [21, 22]. Here, we fix its value the same as that in Refs. [21, 22], i.e. $\delta = 0.557$.

In the calculation, the standard quark model parameters are adopted. Namely, we set $m_u = m_d = 330$ MeV, $m_s = 450$ MeV, $m_c = 1700$ MeV and $m_b = 5000$ MeV for the constituent quark masses. The harmonic oscillator parameter α in the wave function ${}^N\Psi_{LL_z}$ is taken as $\alpha = 0.40$ GeV. The decay constants for π , K and η mesons are taken as $f_\pi = 132$ MeV, $f_K = f_\eta = 160$ MeV, respectively. The masses of the mesons and baryons used in the calculations are adopted from the Particle Data Group [6]. With these parameters, the strong decay properties of the well known heavy-light mesons and charmed baryons have been described reasonably [21–24].

IV. RESULTS AND DISCUSSIONS

A. $\Xi_c^*(2645)$

$\Xi_c^*(2645)$ and Ξ_c' are the two lowest states in the Ξ_c' -type charm-strange baryons. They are assigned to the two S -wave states, $|\Xi_c' {}^2S \frac{1}{2}^+\rangle$ and $|\Xi_c' {}^4S \frac{3}{2}^+\rangle$, respectively. The decay widths of $\Xi_c^*(2645) \rightarrow \Xi_c \pi$ are calculated. The results are listed in Tab. VI, from which we find that our predictions are in good agreement with the experimental data [6], and compatible with other theoretical predictions [18, 19, 35–38].

Σ_b and Σ_b^* (Ξ_b' and Ξ_b^*) are counterparts of Ξ_c' and $\Xi_c^*(2645)$, respectively. Recently, the improved measurements of the masses and first measurements of natural widths of the bottom baryon states Σ_b^\pm and $\Sigma_b^{*\pm}$ were reported by CDF Collaboration [25], and a new neutral excited bottom-strange baryon with a mass $m = 5945.0 \pm 0.7 \pm 0.3 \pm 2.7$ MeV was observed by CMS Collaboration [26]. Given the measured mass and decay mode of the newly observed bottom-strange baryon, this state most likely corresponds to Ξ_b^{*0} with $J^P = 3/2^+$. As a by-product, we have calculated the strong decays of the bot-

tom baryons Σ_b^\pm , $\Sigma_b^{*\pm}$ and Ξ_b^{*0} . Our results together with other model predictions and experimental data have been listed in Tab. VII. From the table, it is seen that our predictions are in good agreement with the measurements [25, 26] and the other model predictions [19, 39–42]. It should be pointed out that the strong decay properties of Ξ_b^* were studied in [19, 42], where a little large mass $m \simeq 5960$ MeV was adopted. With the recent measured mass of Ξ_b^{*0} , the predicted decay widths in [19, 42] should be a little smaller than their previous predictions.

TABLE VI: The decay widths (MeV) of the well-established charm-strange baryons $\Xi_c^*(2645)$, $\Xi_c(2790)$ and $\Xi_c(2815)$.

	Notation	Channel	$\Gamma(\text{ours})$	$\Gamma_{\text{total}}(\text{ours})$	$\Gamma_{\text{total}}[19]$	$\Gamma_{\text{total}}[36]$	$\Gamma_{\text{total}}[38]$	$\Gamma_{\text{total}}[37]$	$\Gamma_{\text{total}}[35]$	$\Gamma_{\text{total}}[18]$	$\Gamma_{\text{total}}^{\text{exp}}$
$\Xi_c^*(2645)^0$	$|\Xi_c'^4 S \frac{3}{2}^+\rangle$	$\Xi_c^+ \pi^-$	1.55	2.34	1.08	3.12 ± 0.44	4.2 ± 1.3	3.03 ± 0.1	1.88	2.8 ± 0.2	< 5.5
		$\Xi_c^0 \pi^0$	0.79								
$\Xi_c^*(2645)^+$	$|\Xi_c'^4 S \frac{3}{2}^+\rangle$	$\Xi_c^+ \pi^0$	0.89	2.44	1.13	3.04 ± 0.50	4.2 ± 1.3	3.18 ± 0.1	1.81	2.7 ± 0.2	< 3.1
		$\Xi_c^0 \pi^+$	1.55								
$\Xi_c(2790)^+$	$|\Xi_c^2 P_{\lambda} \frac{1}{2}^-\rangle$	$\Xi_c'^+ \pi^0$	0.92	2.72	9.9					$8.0^{+4.7}_{-3.3}$	< 15
		$\Xi_c'^0 \pi^+$	1.80								
		$\Xi_c^*(2645)^0 \pi^+$	4×10^{-5}								
		$\Xi_c^*(2645)^+ \pi^0$	2×10^{-5}								
$\Xi_c(2790)^0$	$|\Xi_c^2 P_{\lambda} \frac{1}{2}^-\rangle$	$\Xi_c'^+ \pi^-$	1.84	2.77	10.3					$8.5^{+5.0}_{-3.5}$	< 12
		$\Xi_c'^0 \pi^0$	0.93								
		$\Xi_c^*(2645)^+ \pi^-$	4×10^{-5}								
		$\Xi_c^*(2645)^0 \pi^0$	2×10^{-5}								
$\Xi_c(2815)^+$	$|\Xi_c^2 P_{\lambda} \frac{3}{2}^-\rangle$	$\Xi_c'^0 \pi^+$	0.15	1.50	5.3	1.26 ± 0.13			7.67	$3.4^{+2.0}_{-1.4}$	< 3.5
		$\Xi_c'^+ \pi^0$	0.08								
		$\Xi_c^*(2645)^0 \pi^+$	0.83								
		$\Xi_c^*(2645)^+ \pi^0$	0.44								
$\Xi_c(2815)^0$	$|\Xi_c^2 P_{\lambda} \frac{3}{2}^-\rangle$	$\Xi_c'^+ \pi^-$	0.17	1.64	5.5					$3.6^{+2.1}_{-1.5}$	< 6.5
		$\Xi_c'^0 \pi^0$	0.09								
		$\Xi_c^*(2645)^+ \pi^-$	0.87								
		$\Xi_c^*(2645)^0 \pi^0$	0.51								

TABLE VII: The decay widths (MeV) of the ground S -wave bottom baryons Σ_b^\pm , $\Sigma_b^{*\pm}$ and newly observed $\Xi_b^*(5945)^0$.

	Notation	Channel	$\Gamma(\text{ours})$	$\Gamma[19]$	$\Gamma[40]$	$\Gamma[39]$	$\Gamma[41]$	$\Gamma[42]$	Γ_{exp}
$\Sigma_b(5811)^+$	$|\Sigma_b^2 S \frac{1}{2}^+\rangle$	$\Lambda_b^0 \pi^+$	5.9	3.5	6.0	4.35	6.73–13.45	4.82, 4.94	$9.7^{+5.0}_{-3.9}$ [25]
$\Sigma_b(5816)^-$	$|\Sigma_b^2 S \frac{1}{2}^+\rangle$	$\Lambda_b^0 \pi^-$	6.7	4.7	7.7	5.77	6.73–13.45	6.31, 6.49	$4.9^{+4.2}_{-3.2}$ [25]
$\Sigma_b^*(5832)^+$	$|\Sigma_b^4 S \frac{3}{2}^+\rangle$	$\Lambda_b^0 \pi^+$	10.2	7.5	11.0	8.50	10.00–17.74	9.68, 10.06	$11.5^{+3.7}_{-3.7}$ [25]
$\Sigma_b^*(5835)^-$	$|\Sigma_b^4 S \frac{3}{2}^+\rangle$	$\Lambda_b^0 \pi^-$	11.0	9.2	13.2	10.44	10.00–17.74	11.81, 12.34	$7.5^{+3.1}_{-3.2}$ [25]
$\Xi_b^*(5945)^0$	$|\Xi_b'^4 S \frac{3}{2}^+\rangle$	$\Xi_b \pi$	0.6	0.85	...	...	...	1.83, 1.85	2.1 ± 1.7 [26]

B. $\Xi_c(2790)$ and $\Xi_c(2815)$

$\Xi_c(2790)$ and $\Xi_c(2815)$ are two relatively well-determined P -wave charm-strange baryons with quantum numbers $J^P = 1/2^-$ and $3/2^-$, respectively. They were observed in the $\Xi_c' \pi$ and $\Xi_c \pi \pi$ channels, respectively. The Particle Data Group suggests they belong to the same SU(4) multiplet as $\Lambda_c(2593)$ and $\Lambda_c(2625)$, respectively [6]. According to our previous study, $\Lambda_c(2593)$ and $\Lambda_c(2625)$ can be well explained with the $|\Lambda_c^2 P_{\lambda} \frac{1}{2}^-\rangle$ and $|\Lambda_c^2 P_{\lambda} \frac{3}{2}^-\rangle$ assignments [21]. Thus, $\Xi_c(2790)$ and $\Xi_c(2815)$ should correspond to the Ξ_c -type excited states $|\Xi_c^2 P_{\lambda} \frac{1}{2}^-\rangle$ and $|\Xi_c^2 P_{\lambda} \frac{3}{2}^-\rangle$, respectively. With these assignments we have calculated the strong decay properties of $\Xi_c(2790)$ and $\Xi_c(2815)$, which are listed in Tab VI. Our predicted widths are in the range of observations [6] and compatible with other theoretical predictions [18, 19]. On the other hand, $\Xi_c(2790)$ as a dynamically generated resonance having $J^P = 1/2^-$ was also discussed in [43].

Finally it should be pointed out that $\Xi_c(2790)$ and $\Xi_c(2815)$ can not be P_ρ -mode excited states $|\Xi_c^2 P_\rho \frac{1}{2}^-\rangle$ and $|\Xi_c^2 P_\rho \frac{3}{2}^-\rangle$, because these excitations have large partial decay widths into $\Xi_c \pi$ and $\Lambda_c^+ \bar{K}$ channels (see Fig. 1), which disagrees with the observations. The strong decay properties of the P_ρ -mode excited states have been shown in Fig. 1. We advise experimentalists to search these missing P -wave states in $\Xi_c \pi$, $\Lambda_c^+ \bar{K}$ and $\Xi_c^*(2645) \pi$ invariant mass distributions around the energy region (2.8 ~ 2.9) GeV.

C. $\Xi_c(2930)$

$\Xi_c(2930)$ is not well-established. It was only seen by BaBar in the $\Lambda_c^+ \bar{K}$ invariant mass distribution in an analysis of $B^- \rightarrow \Lambda_c^+ \bar{K}^- K^-$. The mass analysis of the charm-strange baryon spectrum indicates that $\Xi_c(2930)$ can be assigned to the first orbital ($1P$) excitation of Ξ_c' or the first radial ($2S$)

excitation of Ξ_c (see Tab. III) [16, 17].

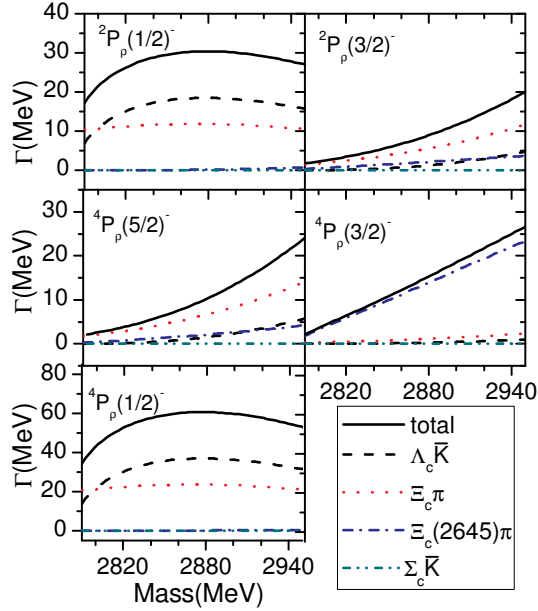


FIG. 1: (Color online) The strong decay properties of the P_ρ -mode excitations of Ξ_c .

We have analyze the strong decay properties of all the first P -wave excitations of Ξ_c' and the first radial ($2S$) excitations of Ξ_c , which have been shown in Fig. 2 and 3.

As a whole, $\Xi_c(2930)$ is most likely to be the first orbital ($1P$) excitation of Ξ_c' with $J^P = 1/2^-$, favors $|\Xi_c' 4P_\lambda 1/2^- \rangle$ or $|\Xi_c' 2P_\lambda 1/2^- \rangle$. To confirm $\Xi_c(2930)$ and finally classify it, further observations in the $\Xi_c'\pi$, $\Xi_c\pi$, $\Lambda_c^+\bar{K}$ invariant mass distributions and measurements of these partial decay ratios are very crucial in experiments.

D. $\Xi_c(2980)$

$\Xi_c(2980)$ with a width of ~ 40 MeV was first found by Belle Collaboration in the $\Lambda_c^+\bar{K}\pi$ channel, and then confirmed by BaBar with large significances in the intermediate-resonant $\Sigma_c(2455)\bar{K}$ and nonresonant $\Lambda_c^+\bar{K}\pi$ decay channels. Belle also observed a resonance structure around 2.97 GeV with a smaller width of ~ 18 MeV in the $\Xi_c^*(2645)\pi$ decay channel in a separate study [3], which is often considered as the same state of $\Xi_c(2980)$. It should be pointed out that BaBar and Belle had analyzed the $\Lambda_c^+\bar{K}$ and $\Xi_c\pi$ invariant mass distributions, respectively, but they did not find any structures around 2.98 GeV, which indicates that these partial decay width are too small to be observed or these decay modes are forbid-

den. Firstly, we can exclude the first radial ($2S$) excitations of Ξ_c as assignments to $\Xi_c(2930)$ for the decay channel $\Lambda_c^+\bar{K}$ of these states is forbidden (see Fig. 3).

In the first P -wave excitations of Ξ_c' , we have noted that the decay modes $\Lambda_c^+\bar{K}$ and $\Xi_c\pi$ for the P_ρ -mode excited states, $2P_\rho(1/2^-)$ and $2P_\rho(3/2^-)$, are forbidden, thus, these states as assignments to $\Xi_c(2930)$ should be excluded. Furthermore, it is found that the strong decays of $2P_\lambda(3/2^-)$ and $4P_\lambda(5/2^-)$ are governed by the $\Xi_c\pi$ channel, and the $\Xi_c^*(2645)\pi$ decay mode dominates the decay of $4P_\lambda(3/2^-)$. They might be hard observed by BaBar for their small $\Lambda_c^+\bar{K}$ branching ratios. Given the decay modes and decay widths, two $J^P = 1/2^-$ states $4P_\lambda(1/2^-)$ and $2P_\lambda(1/2^-)$ seem to be the possible assignments to $\Xi_c(2930)$. Considering $\Xi_c(2930)$ as the $2P_\lambda(1/2^-)$, from the figure we find that its decays are dominated by $\Lambda_c^+\bar{K}$ and $\Xi_c'\pi$, and the other partial decay widths are negligibly small. Its total width and the partial decay width ratio between $\Lambda_c^+\bar{K}$ and $\Xi_c'\pi$ are

$$\Gamma = 10.6\text{MeV}, \quad \frac{\Gamma(\Lambda_c^+\bar{K})}{\Gamma(\Xi_c'\pi)} \approx 1.1. \quad (11)$$

And considering $\Xi_c(2930)$ as the $4P_\lambda(1/2^-)$, we see that the $\Lambda_c^+\bar{K}$ governs the decays of $\Xi_c(2930)$, and the other two decay channels $\Xi_c\pi$ and $\Xi_c'\pi$ have sizeable widths. The calculated total width and partial decay width ratios are

$$\Gamma = 16.7\text{MeV}, \quad \frac{\Gamma(\Lambda_c^+\bar{K})}{\Gamma(\Xi_c\pi)} \approx 2.8, \quad \frac{\Gamma(\Lambda_c^+\bar{K})}{\Gamma(\Xi_c'\pi)} \approx 4.6. \quad (12)$$

den. Although $\Xi_c(2980)$ is well-established in experiments, its quantum numbers are still unknown. Recently, Ebert *et al.* calculated the mass spectra of heavy baryons in the heavy-quark-light-diquark picture in the framework of the QCD-motivated relativistic quark model, they suggested $\Xi_c(2980)$ could be assigned to the first radial ($2S$) excitation of Ξ_c' with $J^P = 1/2^+$ [16], which also consists with their early mass analysis [17]. Cheng *et al.* also discussed the possible classification of $\Xi_c(2980)$. They considered that $\Xi_c(2980)$ might be the first radial ($2S$) excitation of Ξ_c with $J^P = 1/2^+$ [18].

We have analyzed the strong decay properties of the first radial ($2S$) excitations of both Ξ_c and Ξ_c' , which have been shown in Figs. 3 and 4, respectively. From the figures, it is seen that the $2S$ excitations of both Ξ_c and Ξ_c' have narrow decay widths (< 2 MeV), which are at least an order smaller than those of $\Xi_c(2980)$. Furthermore, the decay modes of these first radial excitations are in disagreement with the observations of $\Xi_c(2980)$. Thus, the $2S$ excitations of both Ξ_c and Ξ_c' are excluded as assignments to $\Xi_c(2980)$ in present work. Our conclusion is in agreement with that of 3P_0 calculations [19].

$\Xi_c(2980)$ might be one of the $N = 2$ shell orbital excitations of Ξ_c since the masses of these states are close to

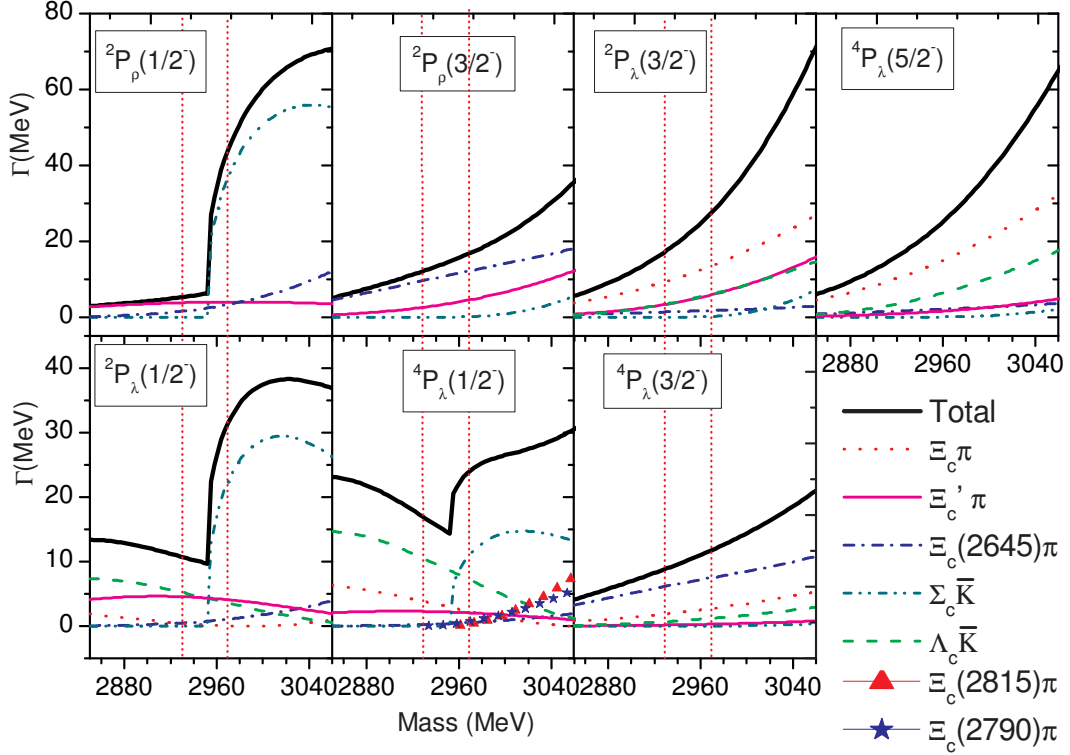


FIG. 2: (Color online) The strong decay properties of the first orbital (1P) excitations of Ξ'_c .

2980 MeV. Their calculated partial decay widths and total widths have been shown in Figs. 5 and 6. It is seen that the $P_A(1/2^+, 3/2^+, 5/2^+)$, $D_A(5/2^+, 7/2^+)$, $D_{\rho\rho}(3/2^+, 5/2^+)$ and $D_{\lambda\lambda}(3/2^+, 5/2^+)$ states have too narrow decay widths to compare with the observations of $\Xi_c(2980)$. Furthermore, although the decay widths of $D_A(1/2^+, 3/2^+)$ are compatible with the measurement, their decay modes are dominated by $\Lambda_c^+ \bar{K}$ and $\Xi_c \pi$, which disagrees with the observations as well. As a whole, all the states shown in Figs. 5 and 6 are not good assignments to $\Xi_c(2980)$ either their decay widths are too narrow to compare with the observations or their decay modes disagree with the observations.

The P_ρ -mode states, $^2P_\rho(1/2^-)$ and $^2P_\rho(3/2^-)$, in the first P -wave excitations of Ξ'_c could be candidates of $\Xi_c(2980)$ (see Fig. 2). We have noted that excitation of the λ variable unlike excitation in ρ involves the excitation of the “odd” heavy quark. The P_ρ -mode excitation of charm-strange baryon is ~ 70 MeV heavier than the P_λ -mode [44, 45]. According to our analysis in IV C, $\Xi_c(2930)$ might be assigned to a P_λ -mode excitation of Ξ'_c . Thus, the expected mass of the P_ρ -mode excitation is ~ 3.0 GeV, which is comparable with that of $\Xi_c(2980)$. As the $^2P_\rho(1/2^-)$ and $^2P_\rho(3/2^-)$ candidates, respectively, the partial decay widths and total width of $\Xi_c(2980)$ have been listed in Tab. VIII.

If the resonance structure around 2.97 GeV in the

$\Xi_c^*(2645)\pi$ decay channel is the same state, $\Xi_c(2980)$, observed in $\Lambda_c^+ \bar{K}\pi$ decay channel, $\Xi_c(2980)$ is most likely to be the $J^P = 1/2^-$ excited state $^2P_\rho(1/2^-)$. The reasons are as follows. (i) The decay modes of $^2P_\rho(1/2^-)$ are in agreement with the observations. From Tab. VIII, we see that the strong decays of $^2P_\rho(1/2^-)$ are dominated by $\Sigma_c \bar{K}$, and the partial decay width of $\Xi_c^*(2645)\pi$ is sizeable as well. The $\Lambda_c^+ \bar{K}\pi$ final state mainly comes from an intermediate process in $\Xi_c(2980) \rightarrow \Sigma_c \bar{K} \rightarrow \Lambda_c^+ \bar{K}\pi$. (ii) The total decay width

$$\Gamma \simeq 44 \text{ MeV}, \quad (13)$$

is in good agreement with the data. (iii) The decay channels $\Xi_c \pi$, $\Lambda_c^+ \bar{K}$ and $\Sigma_c^*(2520) \bar{K}$ of $^2P_\rho(1/2^-)$ are forbidden, which can naturally explain why these decay channels were not observed by Belle and BaBar. It should be mentioned that the same J^P quantum number (i.e. $J^P=1/2^-$) for $\Xi_c(2980)$ is also suggested in [43], where the $\Xi_c(2980)$ is considered as a dynamically generated resonance.

We have noted that the total width of $\Xi_c(2980)$ measured by Belle and BaBar in the $\Lambda_c^+ \bar{K}\pi$ channel is about two times larger than that measured by Belle in the $\Xi_c^*(2645)\pi$ decay channel in a separate study. Thus, the resonance with a mass $m \simeq 2970$ MeV [denoted by $\Xi_c(2970)$ in this work] observed in the $\Xi_c^*(2645)\pi$ decay channel might be a different resonance from the $\Xi_c(2980)$ observed in the $\Lambda_c^+ \bar{K}\pi$ channel, al-

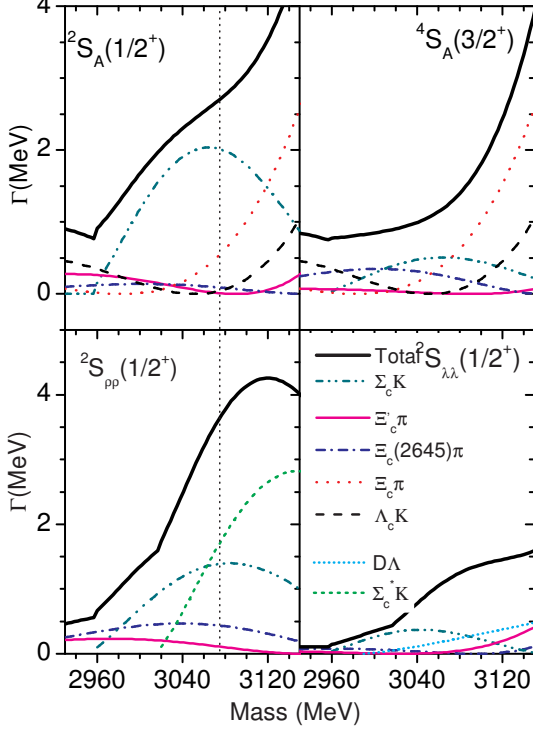


FIG. 3: (Color online) The strong decay properties of the $L = 0$ excitations of Ξ_c .

though they have comparable masses. According to our analysis, the $\Xi_c(2970)$ observed in the $\Xi_c^*(2645)\pi$ channel and $\Xi_c(2980)$ observed in the $\Lambda_c^+\bar{K}\pi$ channel might be assigned to the ${}^2P_\rho(1/2^-)$ and ${}^2P_\rho(3/2^-)$ excitations, respectively. If the ${}^2P_\rho(3/2^-)$ is considered as the $\Xi_c(2970)$ observed in the $\Xi_c^*(2645)\pi$ channel, its total decay width

$$\Gamma \simeq 16 \text{ MeV}, \quad (14)$$

and dominant decay channel $\Xi_c^*(2645)\pi$ are in good agreement with the observations (see Tab. VIII). Furthermore, it is interestingly found that when the ${}^2P_\rho(1/2^-)$ and ${}^2P_\rho(3/2^-)$ excitations are considered as the resonances observed in the $\Lambda_c^+\bar{K}\pi$ and $\Xi_c^*(2645)\pi$, respectively, we can naturally explain why the width measured in the $\Xi_c(2645)^*\pi$ channel is about a factor 2 smaller than that measured in the $\Lambda_c^+\bar{K}\pi$ channel.

In brief, the $\Xi_c(2970)$ observed in the $\Xi_c^*(2645)\pi$ final state is most likely a different state from the $\Xi_c(2980)$ observed in the $\Lambda_c^+\bar{K}\pi$ final state. The $\Xi_c(2980)$ and $\Xi_c(2970)$, as two largely overlapping resonances, favor to be classified as the $|\Xi_c' {}^2P_\rho(1/2^-)\rangle$ and $|\Xi_c' {}^2P_\rho(3/2^-)\rangle$, respectively. Of course, for the uncertainties of the data we can not exclude the $\Xi_c(2970)$ and $\Xi_c(2980)$ as the same resonance, which favors to be assigned to the $|\Xi_c' {}^2P_\rho(1/2^-)\rangle$. To finally clarify whether the $\Xi_c(2970)$ observed in $\Xi_c^*(2645)\pi$ is the same resonance observed in the $\Lambda_c^+\bar{K}\pi$ channel or not, we expect to measure the partial width ratio $\Gamma[\Xi_c^*(2645)\pi] : \Gamma(\Sigma_c\bar{K})$ further. If there is only one resonance assigned to $|\Xi_c' {}^2P_\rho(1/2^-)\rangle$, the ra-

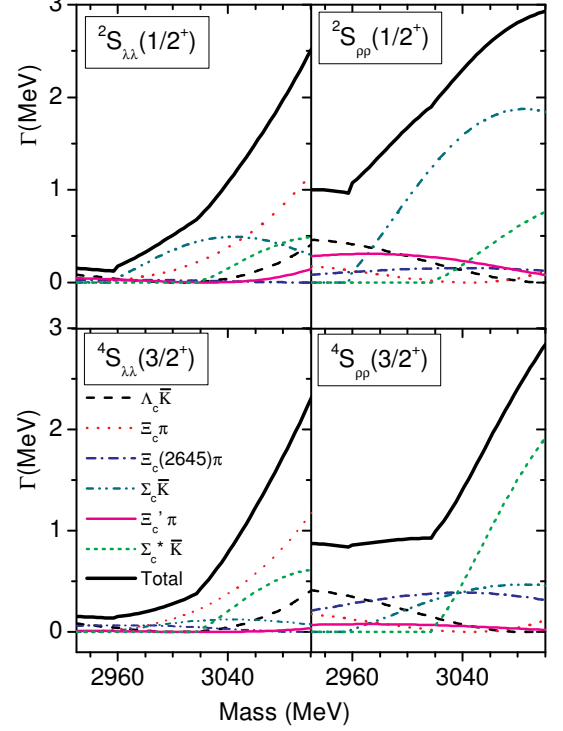


FIG. 4: (Color online) The strong decay properties of the first radial ($2S$) excitations of Ξ_c .

tio $\Gamma[\Xi_c^*(2645)\pi] : \Gamma(\Sigma_c\bar{K})$ might be ~ 0.08 . Otherwise, if the $\Xi_c(2980)$ and $\Xi_c(2970)$ corresponds two overlapping resonances $|\Xi_c' {}^2P_\rho(1/2^-)\rangle$ and $|\Xi_c' {}^2P_\rho(3/2^-)\rangle$, respectively, the ratio might be $\Gamma[\Xi_c^*(2645)\pi] : \Gamma(\Sigma_c\bar{K}) \simeq 0.41$.

TABLE VIII: The partial decay widths and total width (MeV) for $\Xi_c(2980)$ as the ${}^2P_\rho(1/2^-)$ and ${}^2P_\rho(3/2^-)$ excitations of Ξ_c' , respectively.

	$\Sigma_c\bar{K}$	$\Xi_c^*(2645)\pi$	$\Xi_c'\pi$	total
${}^2P_\rho(1/2^-)$	37	3	4	44
${}^2P_\rho(3/2^-)$	0.1	12	4	16

E. $\Xi_c(3080)$

$\Xi_c(3080)^+$ and its isospin partner state $\Xi_c(3080)^0$ were first observed by Belle in the $\Lambda_c^+K^-\pi^+$ and $\Lambda_c^+K^0\pi^-$ final state, respectively. The existence of $\Xi_c(3080)^{+,0}$ has been confirmed by BaBar Collaboration. Furthermore, BaBar's analysis shows that most of the decay of $\Xi_c(3080)^+$ proceeds through the intermediate resonant modes $\Sigma_c(2455)^{++}K^-$ and $\Sigma_c(2520)^{++}K^-$ with roughly equal branching fractions.

Although $\Xi_c(3080)$ has been established in experiments, its quantum is still unclear. Recently, Ebert *et al.* suggested

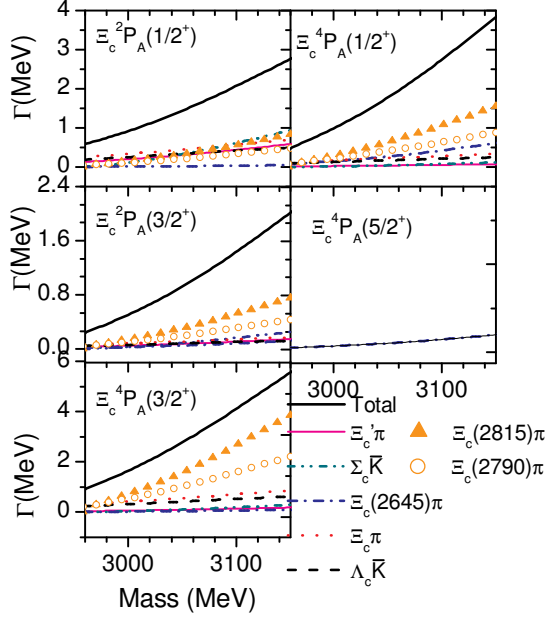


FIG. 5: (Color online) The strong decay properties of the P_A -mode excitations of Ξ_c .

$\Xi_c(3080)$ might be classified as the second orbital ($1D$) excitations of Ξ_c with $J^P = 5/2^+$ according to their mass calculations in the QCD-motivated relativistic quark model. Cheng *et al.* discussed the possible classification of $\Xi_c(3080)$ as well. They suggested that $\Xi_c(3080)$ might be the second orbital ($1D$) excitation of Ξ_c with $J^P = 3/2^+$ or $J^P = 5/2^+$. More possible assignments to the $\Xi_c(3080)$ were suggested by Chen *et al.* in their 3P_0 strong decay analysis [19].

BaBar's observations provide us two very important constraints on the assignments to $\Xi_c(3080)$: (i) the strong decay is governed by both $\Sigma_c(2455)\bar{K}$ and $\Sigma_c(2520)\bar{K}$, (ii) and the partial width ratio $\Gamma(\Sigma_c(2455)\bar{K})/\Gamma(\Sigma_c(2520)\bar{K}) \simeq 1$. We analyzed the strong decay properties of all the $N = 2$ shell excitations of both Ξ_c and Ξ'_c , which were shown in Figs. 3–8. From the figures we find that only the $|\Xi_c^2 S_{\rho\rho} 1/2^+\rangle$ (i.e., the first radial ($2S$) excitation of Ξ_c) satisfies the two constraints of BaBar's observations at the same time: (i) at $m \simeq 3.08$ GeV the strong decays of $|\Xi_c^2 S_{\rho\rho} 1/2^+\rangle$ are dominated by $\Sigma_c(2455)\bar{K}$ and $\Sigma_c(2520)\bar{K}$, the partial other two decay modes $\Xi_c^*(2645)\pi$ and $\Xi'_c\pi$ only contribute a very small partial width to the decay, (ii) and the predicted partial width ratio between $\Sigma_c(2455)\bar{K}$ and $\Sigma_c(2520)\bar{K}$ is

$$\frac{\Gamma[\Sigma_c(2455)\bar{K}]}{\Gamma[\Sigma_c(2520)\bar{K}]} \simeq 0.8. \quad (15)$$

Furthermore, if the $|\Xi_c^2 S_{\rho\rho} 1/2^+\rangle$ is considered as an assignment to $\Xi_c(3080)$, the predicted total width

$$\Gamma \simeq 4 \text{ MeV} \quad (16)$$

is also in good agreement with the measurements.

Finally, it should be pointed out that as a candidate of $\Xi_c(3080)$, the mass of $|\Xi_c^2 S_{\rho\rho} 1/2^+\rangle$ consists with the quark model expectations as well. According to our analysis in Sec. VIII, the $\Xi_c(2980)$ (observed in the $\Lambda_c^+ \bar{K} \pi$ final state) and $\Xi_c(2930)$ could be assigned to P_ρ and P_λ -mode excitations of Ξ'_c , respectively. The estimated mass splitting between P_ρ and P_λ -mode excitation in the $N = 1$ shell is

$$\Delta M \simeq \hbar\omega_\rho - \hbar\omega_\lambda \simeq (2980 - 2930) \text{ MeV} = 50 \text{ MeV}. \quad (17)$$

With the above relation, we can estimate the mass splitting between $S_{\rho\rho}$ and $S_{\lambda\lambda}$ excitations in the $N = 2$ shell, which is

$$M(S_{\rho\rho}) - M(S_{\lambda\lambda}) \simeq 2\hbar\omega_\rho - 2\hbar\omega_\lambda \simeq 100 \text{ MeV}. \quad (18)$$

In most of the quark models, the predicted masses for the $S_{\lambda\lambda}$ excitation of Ξ_c are in the range of (2.92 ~ 2.99) GeV (see Tab. II), thus, the mass of $\Xi_c S_{\rho\rho}$ excitation should be in the range of (3.02 ~ 3.09) GeV, which is comparable with the mass of $\Xi_c(3080)$.

As a whole, the mass, decay modes, partial width ratio $\Gamma(\Sigma_c(2455)\bar{K}) : \Gamma(\Sigma_c(2520)\bar{K})$ and total decay width of $|\Xi_c^2 S_{\rho\rho} 1/2^+\rangle$ strongly support it is assigned to $\Xi_c(3080)$.

F. $\Xi_c(3055)^+$

The $\Xi_c(3055)^+$ as a new structure was found by BaBar in the $\Lambda_c^+ \bar{K} \pi$ mass distribution with a statistical significance of 6.4σ . It decays through the intermediate resonant mode $\Sigma_c(2455)^{++} K^-$. BaBar also searched the inclusive $\Lambda_c^+ \bar{K}$ and $\Lambda_c^+ \bar{K} \pi \pi$ invariant mass spectra for evidence of $\Xi_c(3055)^+$, but no significant structure was found. This state has not yet been confirmed by Belle. According to the calculations of the charm-strange baryon spectrum in various quark models, $\Xi_c(3055)$ might be assigned to the second orbital ($1D$) excitation of Ξ_c (see Tab. II).

We have analyzed the strong decay properties of the second orbital excitations of Ξ_c , which have been shown in Figs. 5 and 6. From Fig. 5, we find that the $P_A(1/2^+, 3/2, 5/2^+)$ excitations can be firstly excluded as the candidates of $\Xi_c(3055)^+$ for neither their decay modes nor their decay widths consist with the observations. Furthermore, from Fig. 6 it is seen that the $\Lambda_c^+ \bar{K}$ is one of the main decay modes of $^4D_A(1/2^+, 3/2, 7/2^+)$ and $^2D_A(3/2^+, 5/2^+)$, if the $\Sigma_c(2455)^{++} K^-$ decay mode for these states is observed in experiments, the $\Lambda_c^+ \bar{K}$ decay mode should be observed as well, which disagrees with the observations of BaBar. Thus, these states as assignments to $\Xi_c(3055)^+$ should be excluded. The strong decays of $^4D_A(5/2^+)$, $^2D_{\lambda\lambda}(5/2^+)$ and $^2D_{\rho\rho}(5/2^+)$ are dominated by $\Xi_c^*(2645)\pi$ and $\Sigma_c(2520)\bar{K}$, the partial width of $\Sigma_c(2455)\bar{K}$ is negligibly small, thus, these states can not be considered as candidates of $\Xi_c(3055)^+$ as well.

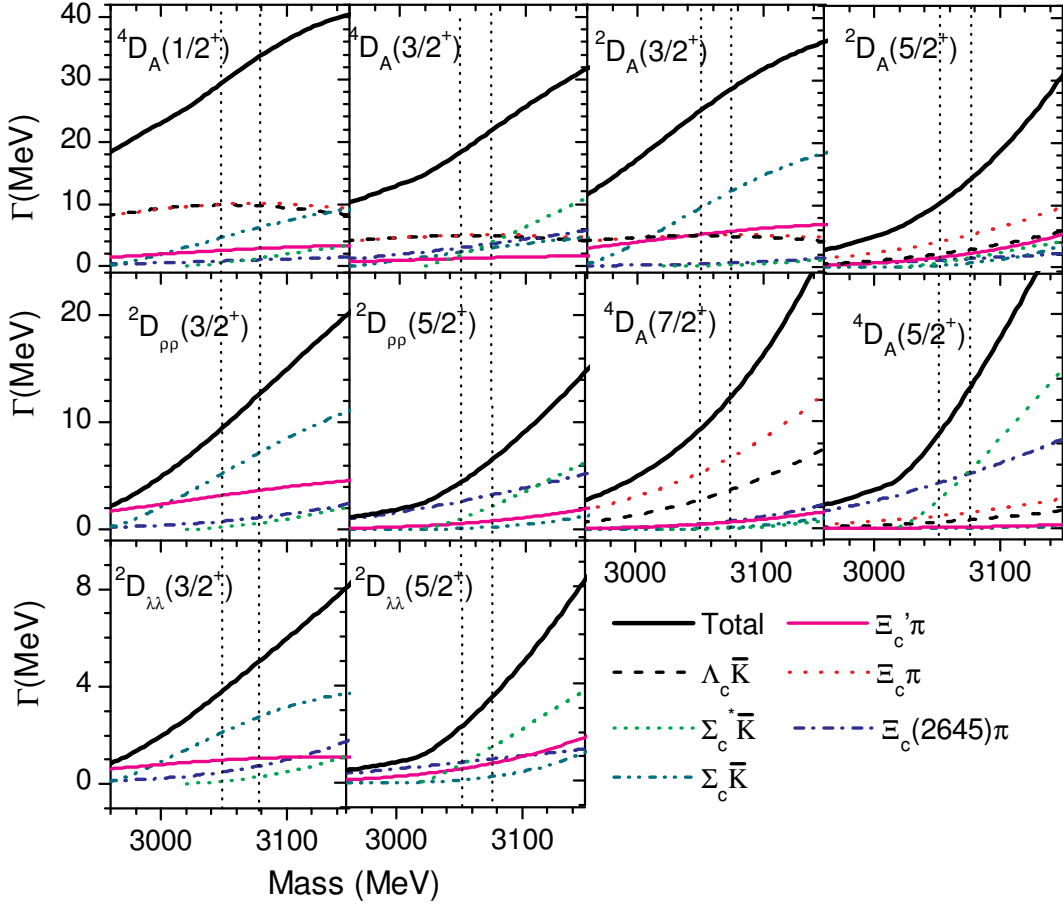


FIG. 6: (Color online) The strong decay properties of the second orbital ($1D$) excitations of Ξ_c . Some decay channels, such as $\Xi_c \eta$, $\Xi_c(2790, 2815)\pi$ are not shown in the figure for their small partial decay widths.

Finally, we find that only two $J^P = 3/2^+$ states $|\Xi_c^2 D_{\lambda\lambda} 3/2^+\rangle$ and $|\Xi_c^2 D_{\rho\rho} 3/2^+\rangle$, might be candidates of the $\Xi_c(3055)$. The partial decay widths and total width of $\Xi_c(3055)$ as the $|\Xi_c^2 D_{\lambda\lambda} 3/2^+\rangle$ and $|\Xi_c^2 D_{\rho\rho} 3/2^+\rangle$ candidates have been listed in Tab. IX, respectively. From the table it is seen that the total widths of both states are compatible with the observations of $\Xi_c(3055)$ within its uncertainties. The strong decays of both states are dominated by $\Sigma_c(2455)\bar{K}$ and the partial width of $\Sigma_c(2520)\bar{K}$ is negligibly small, which can explain why BaBar only observed the intermediate resonant decay mode $\Sigma_c(2455)^{++}K^-$ for $\Xi_c(3055)$. The $\Lambda_c^+\bar{K}$ decay mode is forbidden for both $|\Xi_c^2 D_{\lambda\lambda} 3/2^+\rangle$ and $|\Xi_c^2 D_{\rho\rho} 3/2^+\rangle$, which agrees with the observation that no structures were found around $M(\Lambda_c^+\bar{K}) \simeq 3.05$ GeV. As a whole, $\Xi_c(3055)$ could be assigned to the second orbital ($1D$) excitations of Ξ_c with $J^P = 3/2^+$, our conclusion is in agreement with that of Ebert

et al. according to their mass analysis. However, it is difficult to determine which one can be assigned to $\Xi_c(3055)^+$ in the $|\Xi_c^2 D_{\lambda\lambda} 3/2^+\rangle$ and $|\Xi_c^2 D_{\rho\rho} 3/2^+\rangle$ candidates only according to the strong decay properties. We have noted that $\Xi_c(3080)$ is most likely to be the $\Xi_c S_{\rho\rho}$ assignment. According to various quark model predictions, the mass of the second orbital excitation $\Xi_c D_{\rho\rho}$ should be larger than that of the first radial excitation $\Xi_c S_{\rho\rho}$, which indicates that the mass of $\Xi_c D_{\rho\rho}$ might be larger than 3.08 GeV. From this point of view, the $|\Xi_c^2 D_{\rho\rho} 3/2^+\rangle$ as an assignments to $\Xi_c(3055)^+$ should be excluded. Thus, the $\Xi_c(3055)$ is most likely to be classified as the $|\Xi_c^2 D_{\lambda\lambda} 3/2^+\rangle$ excitation.

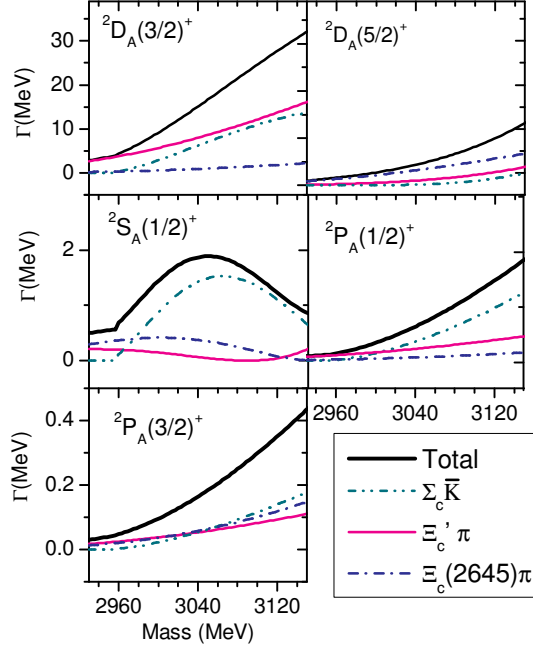


FIG. 7: (Color online) The strong decay properties of the $l_l = l_p = 1$ excitations of Ξ_c' .

TABLE IX: The partial decay widths and total width (MeV) for $\Xi_c(3055)$ as the ${}^2D_{\lambda\lambda}(3/2^+)$ and ${}^2D_{\rho\rho}(3/2^+)$ excitations of Ξ_c , respectively.

	$\Sigma_c \bar{K}$	$\Xi_c^*(2645)\pi$	$\Xi_c' \pi$	$\Sigma_c^* \bar{K}$	$D\Lambda$	total
${}^2D_{\lambda\lambda}(3/2^+)$	2.3	0.5	1.0	0.1	0.1	4.0
${}^2D_{\rho\rho}(3/2^+)$	5.6	0.8	3.3	0.3	—	10.0

G. $\Xi_c(3123)^+$

$\Xi_c(3123)^+$ is another new narrow structure was observed by BaBar in the $\Lambda_c^+ \bar{K} \pi$ final state only with week statistical significance 3.0σ . It decays through a intermediate resonant process in $\Xi_c(3123)^+ \rightarrow \Sigma_c(2520)^{++} K^- \rightarrow \Lambda_c^+ K^- \pi^+$. BaBar also searched $\Xi_c(3123)^+$ in the $\Lambda_c^+ \bar{K}$ and $\Lambda_c^+ \bar{K} \pi \pi$ final states

further, however, they did not find any evidence in these channels. $\Xi_c(3123)^+$ has not yet been confirmed by Belle.

From Tab. II, it is seen that the predicted masses of the second orbital ($1D$) excitations of Ξ_c' in various quark models are $(3.12 \sim 3.17)$ GeV. Thus, the $1D$ excitations of Ξ_c' might be candidates of $\Xi_c(3123)^+$. We have analyzed the strong decay properties of these excitations, which have been shown in Fig. 8.

In these D -wave states, we can first excluded the ${}^2D_{\rho\rho}(3/2^+)$, ${}^4D_{\rho\rho}(1/2^+)$, ${}^2D_{\lambda\lambda}(3/2^+)$, ${}^2D_{\lambda\lambda}(5/2^+)$, ${}^4D_{\lambda\lambda}(1/2^+)$ and ${}^4D_{\lambda\lambda}(7/2^+)$ as assignments to $\Xi_c(3123)^+$ for their partial width of $\Sigma_c(2520)\bar{K}$ is negligibly small compared with that of $\Sigma_c(2455)\bar{K}$ or $\Lambda_c^+ \bar{K}$. Furthermore, we do not consider the ${}^2D_{\rho\rho}(5/2^+)$, ${}^4D_{\rho\rho}(3/2^+)$ and ${}^4D_{\rho\rho}(7/2^+)$ as good candidates of $\Xi_c(3123)^+$ although the $\Sigma_c(2520)\bar{K}$ is their dominant decay channel. The reason is that the $\Lambda_c^+ \bar{K}$ has a large partial width which should be observed by BaBar, however, this decay mode was not observed yet.

Finally, only three excitations ${}^4D_{\lambda\lambda}(3/2^+)$, ${}^4D_{\lambda\lambda}(5/2^+)$ and ${}^4D_{\rho\rho}(5/2^+)$ might be candidates of $\Xi_c(3123)^+$. They decay mainly through $\Sigma_c(2520)\bar{K}$ with a narrow decay width, which is consistent with the observations of $\Xi_c(3123)^+$. To clearly see the decay properties of ${}^4D_{\lambda\lambda}(3/2^+)$, ${}^4D_{\lambda\lambda}(5/2^+)$ and ${}^4D_{\rho\rho}(5/2^+)$, as candidates of $\Xi_c(3123)^+$ their partial decay widths and total width have been listed in Tab. X.

According to our analysis in Sec. IX, $\Xi_c(3055)$ is most likely to be the $|\Xi_c {}^2D_{\lambda\lambda}3/2^+\rangle$ excitation. We have noted that the quark model predicted mass of $\Xi_c' D_{\lambda\lambda}$ is typically ~ 100 MeV heavier than that of $\Xi_c D_{\lambda\lambda}$. Thus, when the $|\Xi_c' {}^4D_{\lambda\lambda}3/2^+\rangle$ or $|\Xi_c' {}^4D_{\lambda\lambda}5/2^+\rangle$ excitation is assigned to the $\Xi_c(3123)$, the quark model predicted mass ~ 3.15 GeV is compatible with the observation. With the relation of $(\hbar\omega_\rho - \hbar\omega_\lambda) \simeq 50$ MeV in Eq.(17), we can further estimate the mass splitting between $D_{\rho\rho}$ and $D_{\lambda\lambda}$ excitations in the $N = 2$ shell, which is

$$M(D_{\rho\rho}) - M(D_{\lambda\lambda}) \simeq 2\hbar\omega_\rho - 2\hbar\omega_\lambda \simeq 100 \text{ MeV}. \quad (19)$$

Thus, the estimated mass of $|\Xi_c' {}^4D_{\rho\rho}5/2^+\rangle$ is ~ 3.25 GeV. Obviously, the $|\Xi_c' {}^4D_{\rho\rho}5/2^+\rangle$ could not be considered as a good assignment to $\Xi_c(3123)$ for its mass is too heavy to compare with the measurement.

It should be pointed out that in second orbital ($1D$) excitations of Ξ_c , the $D_{\rho\rho}$ excitation $|\Xi_c {}^2D_{\rho\rho}5/2^+\rangle$ is also a good assignment to $\Xi_c(3123)$. According to Eq. (19) the mass of the ρ variable excitation $D_{\rho\rho}$ is 100 MeV heavier than the $D_{\lambda\lambda}$ excitation. In Sec. IX, we predicted that $\Xi_c(3055)$ is most likely to be the $|\Xi_c {}^2D_{\lambda\lambda}3/2^+\rangle$ excitation, thus, the estimated masses for $|\Xi_c {}^2D_{\rho\rho}5/2^+\rangle$ might be ~ 3.15 GeV, which are close to the mass of $\Xi_c(3123)$. Its partial decay widths and total width have been listed in Tab. X. From the table it is seen that both

the decay modes and total width of $|\Xi_c {}^2D_{\rho\rho}5/2^+\rangle$ are compatible with the observations of $\Xi_c(3123)$.

As a conclusion, for the scarce experimental information, we can not determine the J^P of $\Xi_c(3123)$. Given the mass, decay mode and total width observed in experiment, $\Xi_c(3123)$ could be assigned to the excitation $|\Xi_c' {}^4D_{\lambda\lambda}3/2^+\rangle$, $|\Xi_c' {}^4D_{\lambda\lambda}5/2^+\rangle$ or $|\Xi_c {}^2D_{\rho\rho}5/2^+\rangle$. Since the $|\Xi_c' {}^4D_{\lambda\lambda}3/2^+\rangle$, $|\Xi_c' {}^4D_{\lambda\lambda}5/2^+\rangle$, and $|\Xi_c {}^2D_{\rho\rho}5/2^+\rangle$ have a comparable mass, the $\Xi_c(3123)$ structure might correspond to several highly overlapping states around

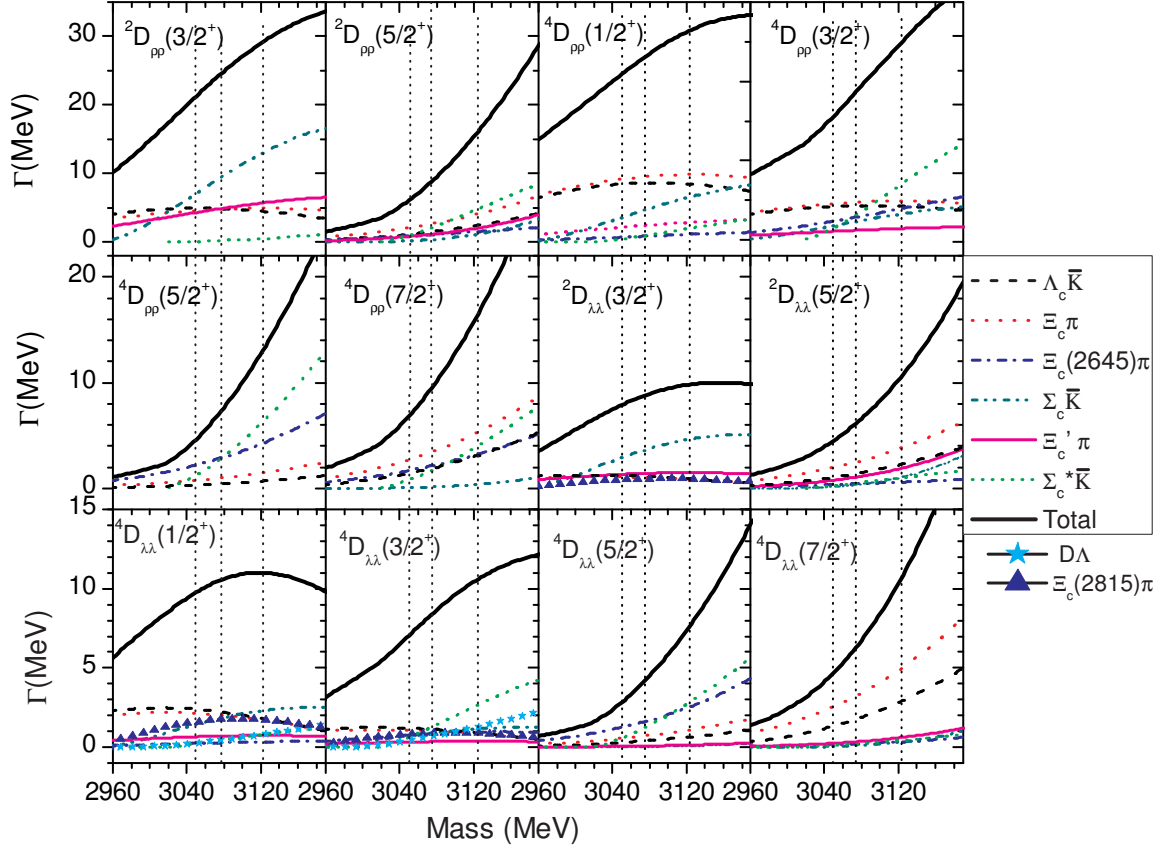


FIG. 8: (Color online) The strong decay properties of the second orbital ($1D$) excitations of Ξ'_c . Some decay channels, such as $\Xi_c\eta$, $\Xi_c(2790, 2815)\pi$ are not shown in the figure for their too narrow partial decay widths to compare with the others'.

3.1 GeV. From Tab. X, it is seen that the partial decay width ratios $\Gamma(\Sigma_c \bar{K}) : \Gamma(\Sigma'_c \bar{K})$, $\Gamma(\Xi'_c 2645\pi) : \Gamma(\Sigma'_c \bar{K})$ and $\Gamma(\Xi_c \pi) : \Gamma(\Sigma'_c \bar{K})$ for these possible assignments to $\Xi_c(3123)$ are very

different, thus, the measurements of these ratios are important to understand the nature of $\Xi_c(3123)$.

TABLE X: The partial decay widths and total width (MeV) for $\Xi_c(3123)$ as the $\Xi'_c 4D_{\lambda\lambda}(3/2^+)$, $\Xi'_c 4D_{\lambda\lambda}(5/2^+)$, $\Xi'_c 4D_{\rho\rho}(5/2^+)$ and $\Xi_c 2D_{\rho\rho}(5/2^+)$ excitations, respectively.

	$\Sigma_c \bar{K}$	$\Xi'_c(2645)\pi$	$\Xi_c \pi$	$\Sigma'_c \bar{K}$	$\Lambda_c \bar{K}$	$\Xi'_c \pi$	$\Xi_c(2815)\pi$	$\Xi_c(2790)\pi$	$D\Lambda$	total	$\frac{\Gamma(\Sigma_c \bar{K})}{\Gamma(\Sigma'_c \bar{K})}$	$\frac{\Gamma(\Xi'_c(2645)\pi)}{\Gamma(\Sigma'_c \bar{K})}$	$\frac{\Gamma(\Xi_c \pi)}{\Gamma(\Sigma'_c \bar{K})}$
$\Xi'_c 4D_{\lambda\lambda}(3/2^+)$	1.2	1.0	0.9	2.6	0.9	0.4	0.9	0.4	1.2	10.5	0.46	0.38	0.35
$\Xi'_c 4D_{\lambda\lambda}(5/2^+)$	0.07	2.6	1.1	2.9	0.6	0.1	0.1	0.05	0.09	7.8	0.02	0.90	0.38
$\Xi'_c 4D_{\rho\rho}(5/2^+)$	0.1	4.3	1.5	6.3	0.7	0.2	0	0	0	13.0	0.01	0.68	0.24
$\Xi_c 2D_{\rho\rho}(5/2^+)$	0.8	4.5	0	4.8	0	1.5	0	0	0	11.6	0.17	0.94	0

V. SUMMARY

In the chiral quark model framework, the strong decays of charm-strange baryons are studied. As a by-product we also

calculate the strong decays of the S -wave bottom baryons Σ_b^\pm , $\Sigma_b^{*\pm}$, Ξ'_b and Ξ_b^* . We obtain good descriptions of the strong de-

cay properties of the well-determined charm-strange baryons $\Xi_c^*(2645)$, $\Xi_c(2790)$ and $\Xi_c(2815)$. Furthermore, the calculated strong decay widths of Σ_b^\pm , $\Sigma_b^{*\pm}$, and Ξ_b^* are in good agreement with the recent measurements.

$\Xi_c(2930)$, if it could be confirmed in experiments, might be the first P -wave excitations of Ξ_c' with $J^P = 1/2^-$. $|\Xi_c' {}^2P_{\lambda}1/2^- \rangle$ and $|\Xi_c' {}^4P_{\lambda}1/2^- \rangle$ could be candidates of $\Xi_c(2930)$ according to the present data. Further observations in the $\Xi_c'\pi$, $\Xi_c\pi$, $\Lambda_c^+\bar{K}$ invariant mass distributions and measurements of these partial decay ratios are very crucial to confirm $\Xi_c(2930)$ and classify it finally.

$\Xi_c(2980)$ might correspond to two different P_ρ -mode exci-

tations of Ξ_c' : one resonance is the broader ($\Gamma \simeq 44$ MeV) excitation $|\Xi_c' {}^2P_{\rho}1/2^- \rangle$, which was observed in the $\Lambda_c^+\bar{K}\pi$ final state by BaBar and Belle, and the other resonance is the narrower ($\Gamma \simeq 16$ MeV) excitation $|\Xi_c' {}^2P_{\rho}3/2^- \rangle$, which was observed in the $\Xi_c^*(2645)\pi$ channel by Belle in a separate study. If the structures were observed in the $\Lambda_c^+\bar{K}\pi$ and $\Xi_c^*(2645)\pi$ final states correspond to the same state $\Xi_c(2980)$, which could only be assigned to the $|\Xi_c' {}^2P_{\rho}1/2^- \rangle$ excitation. To finally clarify whether the $\Xi_c(2970)$ observed in $\Xi_c^*(2645)\pi$ is the same state observed in the $\Lambda_c^+\bar{K}\pi$ channel or not, we expect to measure the partial width ratio $\Gamma[\Xi_c^*(2645)\pi] : \Gamma(\Sigma_c\bar{K})$ further.

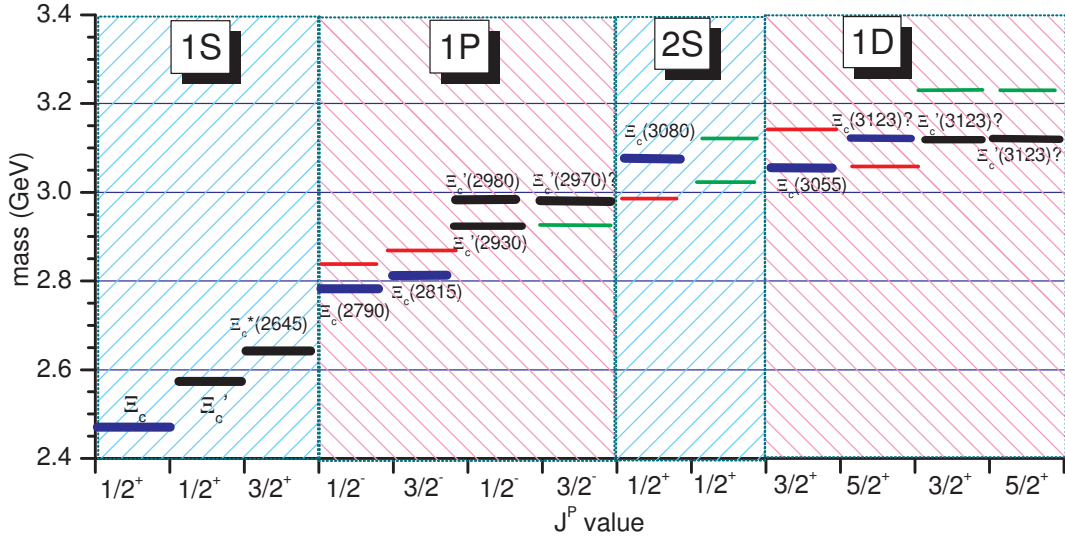


FIG. 9: (Color online) The charm-strange baryon spectrum up to $N = 2$ shell according to our predictions. In $1P$, $2S$ and $1D$ excitations, there are two lines for each J^P value, which correspond to the masses of the excitations of ρ variable (upper line) and λ variable (lower line), respectively. The mass gap between the λ variable excitation and the ρ variable excitation is assumed to be 50 MeV for the $1P$ states, and 100 MeV for the $2S$ and $1D$ states. The thin lines stand for the states unobserved in experiments. In the $1P$ ($1D$) excitations, the first two J^P values are for the excitations of Ξ_c , while the last two J^P values are for the excitations of Ξ_c' . In $2S$ excitations, the first J^P value is for the excitations of Ξ_c , while the second J^P value is for the excitations of Ξ_c' .

$\Xi_c(3080)$ favors to be identified as the first radial excitation $|\Xi_c {}^2S_{\rho\rho}1/2^+ \rangle$. The width, decay modes and ratio $\Gamma(\Sigma_c(2455)\bar{K})/\Gamma(\Sigma_c(2520)\bar{K}) \simeq 0.8$ are in good agreement with the observations. As a assignment to $\Xi_c(3080)$, the mass of $|\Xi_c {}^2S_{\rho\rho}1/2^+ \rangle$ is also consistent with the quark model expectations.

Given the mass, decay modes and decay width, $\Xi_c(3055)$ is most likely to be classified as the second orbital Ξ_c excitation $|\Xi_c {}^2D_{\lambda\lambda}3/2^+ \rangle$. To confirm it in experiments, more observa-

tions in the $\Sigma_c\bar{K}$, $\Xi_c'\pi$ and $\Xi_c^*(2645)\pi$ channels are needed.

$\Xi_c(3123)$ is most likely to be the second orbital ($1D$) excitations of the charm-strange baryon with $J^P = 3/2^+$ or $5/2^+$. It could be assigned to the Ξ_c' excitation $|\Xi_c' {}^4D_{\lambda\lambda}3/2^+ \rangle$ or $|\Xi_c' {}^4D_{\lambda\lambda}5/2^+ \rangle$. For the scarce experiment information about $\Xi_c(3123)$, we can not exclude it as the assignment to the Ξ_c excitation $|\Xi_c {}^2D_{\rho\rho}5/2^+ \rangle$. Since the $|\Xi_c' {}^4D_{\lambda\lambda}3/2^+ \rangle$, $|\Xi_c' {}^4D_{\lambda\lambda}5/2^+ \rangle$ and $|\Xi_c {}^2D_{\rho\rho}5/2^+ \rangle$ have a comparable mass, the $\Xi_c(3123)$ structure might correspond to several largely over-

lapping resonances. To good understand $\Xi_c(3123)$ structure, further observations in the $\Xi_c^*(2645)\pi$, $\Sigma_c^*\bar{K}$ and $\Xi_c\pi$ channels are expected.

Finally, according to our predictions we establish a spectroscopy for the observed charm-strange baryons, which is shown in Fig. 9. We also estimate the masses of the charm-strange baryons with different variable (λ or ρ) excitation from these newly observed states in experiments, which are given in Fig. 9. These missing states might be found in future experiments. To provide helpful information for search for the missing charm-strange baryons, in Figs. 1–8 our predictions of their strong decay properties have been shown as well.

Acknowledgements

This work is supported, in part, by the National Natural Science Foundation of China (11075051), Program for Changjiang Scholars and Innovative Research Team in University (IRT0964), the Program Excellent Talent Hunan Normal University, and the Hunan Provincial Natural Science Foundation (11JJ7001).

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